Safety Impact Assessment of New York City Connected Vehicle Pilot Safety Applications

Final Report

Final Report — May 2022

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13. ABSTRACT (Maximum 200 words) This report presents the methodology and results of the safety impact assessment of five vehicle-to-vehicle (V2V) and four vehicle-to-infrastructure (V2I) safety applications that were deployed in New York City's Connected Vehicle Pilot site. This assessment was based on the naturalistic driving experience of 3,000 vehicles that were equipped with these applications, spanning from January through December 2021. The V2V applications included forward collision warning, emergency electronic brake light, lane change warning, blind spot warning, and intersection movement assist. Posted speed, curve speed, and speed in work zone compliance and red light violation warning comprised the V2I applications. The deployed vehicles experienced a total of 160,289 alert events from the nine safety applications combined. There were 107,609 (67%) alerts by V2I applications and 52,680 (33%) by V2V applications. Of all these events, 65,231 (41%) alerts were silent and 95,058 (59%) alerts were active. The analysis identified and statistically described vehicle/driver response measures after alert onset for each application, including statistical tests to reveal any statistically-significant differences in any of these measures between silent and active alerts. Response to active alerts showed a decrease in speed non-compliance, red light violation rate, rear-end near-crash rate, lane change rate, and unsafe lane change rate.				
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APPROXIMATE CONVERSIONS TO SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t
oz	ounces	28.35	grams	g
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa
APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
mL	milliliters	0.034	fluid ounces	fl oz
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
g	grams	0.035	ounces	oz
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl

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List of Acronyms

Abbreviation	Term
ASD	Aftermarket Safety Device
BSM	Basic Safety Message
BSW	Blind Spot Warning
CA	Control group After
CB	Control group Before
CSPDCOMP	Curve Speed Compliance
CV	Connected Vehicle
CVP	Connected Vehicle Pilot
DSRC	Dedicated Short-range Communications
ECZ	Entered Conflict Zone
EEBL	Emergency Electronic Brake Light
ER	Exposure Ratio
EVACINFO	Emergency Communications and Evacuation Information
FCW	Forward Collision Warning
FDR	Franklin D. Roosevelt
HV	Host Vehicle
IMA	Intersection Movement Assist
ITS JPO	Intelligent Transportation Systems Joint Program Office
LCW	Lane Change Warning
LVD	Lead Vehicle Decelerating
LVM	Lead Vehicle Moving
LVS	Lead Vehicle Stopped
m/s	meter per second
MAP	Map Data Message
mph	mile per hour
NECZ	Not Entered Conflict Zone
NYC	New York City
NYPD	NYC Police Department
OVCCLEARANCELIMIT	Oversize Vehicle Compliance
PEDINXWALK	Pedestrian in Crosswalk Warning
PED-SIG	Mobile Accessible Pedestrian Signal System
PID	Pedestrian Interface Device
PR	Prevention Ratio
RLVW	Red Light Violation Warning
RSU	Roadside Unit
RV	Remote Vehicle
SDC	Secure Data Commons
SIM	Safety Impact Methodology

SPaT	Signal Phase and Timing
SPDCOMP	Speed Compliance
SPDCOMPWZ	Speed Compliance in Work Zone
TA	Treatment group After
TB	Treatment group Before
TIM	Traveler Information Message
TMC	Traffic Management Center
TTC	Time-To-Collision
U.S. DOT	United States Department of Transportation
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle

List of Parameters

Parameter	Definition
$\mathbf{A_{HV}}$	HV average deceleration
$\mathbf{Ap}_{HV}$	HV peak deceleration
BRT	Brake Reaction Time
$\mathbf{DTImin}_{HV}$	HV minimum distance to intersection
$\mathbf{\Delta V_{HV}(min)}$	HV minimum speed differential after alert onset
LatGap(0)	Lateral gap between the sides of the HV and RV at alert onset
LonGap(0)	Longitudinal gap between the front of one vehicle to the rear of another vehicle at alert onset
LongGap*(tLEZ)*	Longitudinal gap at time when LatGap becomes Less than or equal to zero after LCW alert onset
PET	Post Encroachment Time
Rdot(0)	Range rate between the RV and HV at alert onset
TaR	Time after Red
TH(0)	Time headway at alert onset
THmin	Minimum time headway after alert onset
TTC(0)	Time to collision at alert onset
TTCmin	Minimum time to collision after alert onset
$\mathbf{TTCZ}_{HV}(0)$	HV time to reach the conflict zone at alert onset
$\mathbf{TTCZ}_{RV}(0)$	RV time to reach the conflict zone at alert onset
$\mathbf{TTI_{HV}(0)}$	HV time-to-intersection stop line at alert onset
$\mathbf{TTImin}_{HV}$	HV minimum time to intersection
$\mathbf{TTI_{RV}(0)}$	RV time-to-intersection stop line at alert onset
TTO(0)	Time to longitudinal overlap between the HV and RV at alert onset
$\mathbf{V_{HV}(0)}$	HV travel speed at alert onset
$\mathbf{V_{HV}(EI)}$	HV speed when entering the intersection
$\mathbf{V_{HV}(min)}$	HV minimum travel speed after alert onset
$\mathbf{V_{RV}(0)}$	RV travel speed at alert onset

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Executive Summary

The Volpe team evaluated the safety impact of the following safety applications on vehicle/driver performance in the New York City Connected Vehicle Pilot (NYC CVP) site, which deployed 3,000 aftermarket safety devices (ASDs) on board NYC agency fleet vehicles and 450 roadside units at signalized intersections and other infrastructure locations:

- Vehicle-to-Infrastructure (V2I) Applications:
  - Speed Compliance (SPDCOMP)
  - Curve Speed Compliance (CSPDCOMP)
  - Speed Compliance in Work Zone (SPDCOMPWZ)
  - Red Light Violation Warning (RLVW)
- Vehicle-to-Vehicle (V2V) Applications:
  - Forward Collision Warning (FCW)
  - Emergency Electronic Brake Light (EEBL)
  - Lane Change Warning (LCW)
  - Blind Spot Warning (BSW)
  - Intersection Movement Assist (IMA)

This evaluation was based on data collected around 160,289 alert events (from equipped vehicles and the infrastructure during the yearlong deployment that comprised a before period from January 1 to May 19, 2021 and an after period from May 20 to December 31, 2021. The experimental design involved a vehicle control group that only received silent alerts (recorded but not observed by drivers) from the safety applications during the before and after periods, and a treatment vehicle group that experienced silent alerts during the before period and active alerts (recorded and observed by drivers) during the after period. The following is a breakdown of the total alert events by:

- Application type: 107,609 (67%) by V2I applications versus 52,680 (33%) by V2V applications
- Alert status: 65,231 (41%) with silent alerts versus 95,058 (59%) with active alerts
- Deployment period: 51,348 (32%) in the before period versus 108,941 (68%) in the after period
- Vehicle group: 10,097 (6%) by the control group versus 150,192 (94%) by the treatment group

Safety Impact Assessment Process

The Volpe team applied the following analysis steps to assess the safety impact of the NYC CVP safety applications:

1. Filter alert events that contained issues with the data that the NYC CVP team collected, processed, and uploaded to the Secure Data Commons database.
2. Assess the validity of safety application alerts in events with good data.
3. Break down the events with valid alerts by treatment and control groups, before and after deployment periods, and silent and active alerts.
4. Identify and statistically describe the initial conditions of events with valid alerts at alert onset for experimental groups.
5. Identify and statistically describe vehicle/driver response measures after alert onset, and conduct statistical tests to reveal any statistically-significant differences in any of these measures between two experimental groups.

6. Assess the effectiveness of the safety applications in improving the various measures of performance for vehicle/driver response to alerts, based on statistically-significant differences between drivers assisted by active alerts and unassisted drivers in events with silent alerts.

Data Filtering

The first two steps of the safety impact assessment process removed events from the analysis due to data issues and invalid alerts. Tables E1 and E2 show the results of this filtering process respectively for V2I and V2V safety applications.

Table E1. Results of Event Filtering Process for V2I Safety Applications

Events with	SPDCOMP		CSPDCOMP		SPDCOMPWZ		RLVW		All V2I Applications	
	Count	%	Count	%	Count	%	Count	%	Count	%
Data Issues	22,846	25.0%	659	15.1%	78	1.7%	2,907	41.1%	26,490	24.6%
Invalid Alerts	8	0.0%	3,674	84.2%	70	1.5%	12	0.2%	3,764	3.5%
Valid Alerts	68,614	75.0%	29	0.7%	4,525	96.8%	4,158	58.8%	77,326	71.9%
Total	91,468	100.0%	4,362	100.0%	4,673	100.0%	7,077	100.0%	107,580	100.0%

Table E2. Results of Event Filtering Process for V2V Safety Applications

Events with	FCW		EEBL		IMA		LCW		BSW		All V2V Applications	
	Count	%	Count	%	Count	%	Count	%	Count	%	Count	%
Data Issues	19,232	52.8%	257	46.7%	6,473	67.0%	1,287	40.8%	1,117	38.6%	28,366	53.8%
Invalid Alerts	14,334	39.4%	46	8.4%	2,337	24.2%	1,076	34.1%	1,453	50.2%	19,246	36.5%
Valid Alerts	2,844	7.8%	247	44.9%	858	8.9%	794	25.2%	325	11.2%	5,068	9.6%
Total	36,410	100.0%	550	100.0%	9,668	100.0%	3,157	100.0%	2,895	100.0%	52,680	100.0%

Excessive speed flag caused the most dominant error in 83% of all V2I events with bad data, which was simply a programming error in the ASDs. Insufficient data points after alert onset, due to recording or storing error in the data acquisition system, contributed to 77% of all V2V events with bad data. The CSPDCOMP application had the most invalid events, with HV not approaching a curve in 87% of all invalid V2I events. The FCW application had the most invalid events, with RV not in HV's path at alert onset or HV passing through RV after alert onset accounting for 64% of all invalid V2V events. Due to the lack of vehicle location information (i.e., GPS coordinates) in alert event data, data issues rather than application errors could have affected the alert validity analysis.

Key Safety Impact Findings

The safety impact analysis normally compares the performance of the treatment group in the before period with silent alerts to the after period with active alerts. During the NYC CVP deployment, the treatment group erroneously received 1,790 active alerts in the before period and 3,622 silent alerts in the after period. These alerts, while valid, would generally be excluded from the safety impact analysis. Consequently, the number of events with silent alerts was much smaller than the number of events with active alerts for most applications (except SPDCOMP) that it inhibited the ability to perform a meaningful statistical comparison of the treatment group performance between the before and after periods. The Volpe team then decided to assess the safety impact of all applications, other than SPDCOMP, by comparing the response between all valid events with silent alerts and all valid events with active alerts, regardless of period (before or after) or vehicle group (treatment or control).

Table E3 provides key results that exhibit statistically-significant difference in vehicle/driver response between events with silent and active alerts for each safety application.

E3. Statistical Results of Safety Impact Assessment

Application	Key Finding	P Value
SPDCOMP	16% increase in speed limit compliance	0.00
RLVW	41% reduction in red light violation rates Reduction in brake reaction time by 0.4 s	0.00 0.01
CSPDCOMP	Reduction in minimum speed by 3.6 m/s Increase in speed differential by 1.5 m/s	0.00 0.00
SPDCOMPWZ	Increase in minimum speed of 0.2 m/s Decrease in speed differential by 0.2 m/s	0.03 0.10
FCW	Reduction in brake reaction time in the Lead Vehicle Decelerating (LVD) scenario by 0.13 s 25% reduction in near-crash rate in the LVD scenario	0.08 0.07
EEBL	Reduction in brake reaction time by 0.4 s Reduction in average deceleration by 0.17 m/s^2	0.03 0.08
LCW	12% reduction in lane change rate 46% reduction in unsafe lane change rate	0.07 0.04
BSW	77% reduction in unsafe lane change rate	0.07
IMA	Reduction in brake reaction time by 1.3 s	0.02

Conclusions

This analysis revealed an increase in speed limit compliance by SPDCOMP, reduction in red light violation rate by RLVW, reduction in near-crash rate in the LVD scenario by FCW, reduction in lane change rate by LCW, and reduction in unsafe lane change rate by LCW and BSW. These changes to vehicle/driver performance in response to alerts from these applications directly lead to potential safety benefits from their deployment. In addition, the reduction in brake reaction time in response to RLVW, FCW, EEBL, and IMA alerts enhances the safety performance of drivers and indirectly contributes to potential safety benefits of these applications.

1 INTRODUCTION

1.1 Background

This report presents the results of the independent safety evaluation of the safety applications deployed in the New York City (NYC) Connected Vehicle Pilot (CVP) site. In September of 2015, the United States Department of Transportation's (U.S. DOT) Intelligent Transportation Systems Joint Program Office (ITS JPO) selected the following three sites to participate in their national CVP deployment Program: NYC, Tampa, and Wyoming.[1] The goal of this program was to spur innovation among early adopters of connected vehicle (CV) technologies and to gain a better understanding of the impact that these technologies might have on traffic safety, mobility, and the environment.

The CVP program consisted of the three following phases:

- Phase 1: Develop concept
- Phase 2: Design, deploy, and test
- Phase 3: Maintain and operate

To satisfy the goal of understanding the impacts of the CVP deployments, the U.S. DOT's Volpe National Transportation Systems Center (Volpe Center) and Texas Transportation Institute performed an independent evaluation at each pilot site. The Volpe Center performed the independent safety evaluation of the safety applications deployed at all three CVP sites. The safety evaluation results produced by the Volpe team for Tampa and Wyoming CVP sites are described in separate reports [1]. On the other hand, the Texas Transportation Institute conducted evaluations on mobility and environmental impacts at the three CVP sites, as well as the national-level evaluations of CV deployments, and evaluated the performance of the overall CVP program.

1.2 NYC CVP Site Overview

The NYC CVP team deployed CV equipment along heavily-traveled, high-crash rate arterials in Manhattan and Brooklyn [2]. This deployment provided an opportunity to observe the operation and performance of safety applications based on CV technologies in a dense, urban transportation system. The NYC CVP site encompassed three distinct areas:

1. The first area, shown in Figure 1, includes a 4-mile segment of Franklin D. Roosevelt (FDR) Drive from 50th Street to 90th Street in the Upper East Side and East Harlem neighborhoods of Manhattan. FDR Drive is a limited-access highway without signalized intersections. This Drive excludes trucks and buses, since it has a number of low overpasses and short-radius curves. In 2014, over-height incidents on FDR drive cost NYC over $2M in delay costs.

[1] https://www.its.dot.gov/pilots/

Source: U.S DOT Volpe Center

Figure 1. Pilot Site Map – FDR Drive

2. The second area, shown in Figure 2, includes four one-way corridors of 1st Avenue, 2nd Avenue, and 5th Avenue from 14th Street to 67th Street, and 6th Avenue from 14th Street to 59th Street in the Midtown and Upper East Side neighborhoods of Manhattan. The segment lengths are 2.6 miles for 1st, 2nd, and 5th avenues, and 2.2 miles for 6th Avenue. These four avenues in Manhattan include 281 signalized intersections. In addition, this area consists of the five two-way, bi-directional cross streets in Midtown Manhattan: 14th, 23rd, 34th, 42nd, and 57th Streets. This area of NYC is a mix of residential and commercial zones, and is made up of high crash-rate arterials. From 2012 to 2014, there were 20 fatalities and over 5,000 injured persons on these corridors alone.

Source: U.S DOT Volpe Center

Figure 2. Pilot Site Map – Manhattan

3. The third area, shown in Figure 3, covers a 1.6-mile segment of Flatbush Avenue in Brooklyn from Tillary Street on the north and Grand Army Plaza near Prospect Park to the south. Flatbush Avenue in Brooklyn includes 28 signalized intersections and experiences a high crash rate (eight fatalities and over 1,100 injured persons in 2012-2014). This area includes two low overpasses with over-height restrictions. It is also incredibly congested; inbound morning traffic on Flatbush Avenue averages only 15 mph.

Source: U.S DOT Volpe Center

Figure 3. Pilot Site Map – Flatbush Avenue

1.2.1 NYC CVP Deployment Goals and Objectives

The primary goals of the NYC CVP deployment were to improve the operating conditions for safer roadways and to reduce the number of and severity of crashes on the roadways. This CVP served as another tool that could be used to further NYC's Vision Zero program to reduce the number of fatalities and injuries resulting from traffic crashes [3]. The secondary goals were to improve the mobility and reliability of travel in the city and the environmental impacts of the transportation system.

The NYC CVP deployment focused on safety improvements for both motorists and non-motorists. Specific objectives of the NYC CVP deployment were to:

- Manage vehicle speeds
- Reduce vehicle-to-vehicle crashes
- Reduce vehicle-to-pedestrian crashes
- Reduce vehicle-to-infrastructure crashes
- Preserve the privacy of CVP deployment participants

1.2.2 Safety Applications

The NYC CVP team deployed CV technology in a systematic approach to alert vehicles of unsafe roadway conditions and to prevent crashes with other vehicles, pedestrians, and bicyclists. Deployed CV devices included aftermarket safety device (ASDs) for vehicles, smartphone-based pedestrian interface devices (PIDs) for pedestrians, and roadside units (RSUs) for signalized intersections and roadside locations.

Table 1 lists the safety applications deployed in the NYC CVP and their communication type, alert urgency level, and the crash hazard that they can help prevent. The functions of these safety applications are defined in Appendix A. There are two types of CV applications, based on either vehicle-to-vehicle (V2V) or vehicle-to-infrastructure (V2I) Dedicated Short-Range Communications (DSRC). V2V applications rely on the communications from other CV-equipped vehicles, while V2I applications are triggered by data from RSUs installed in selected infrastructure locations. There are two different levels of alert urgency that refer to the type of information communicated by the safety applications:

- Imminent warnings induce drivers to respond immediately in order to avoid a potential crash (e.g., a forward collision warning (FCW) application alerts the driver to quickly brake or steer to avoid a rear-end crash).
- Advisory warnings raise awareness of drivers about the surrounding driving environment and help them drive more safely (e.g., recommended travel speed). A driving scenario that triggers an advisory warning may or may not evolve to a crash-imminent scenario, depending on the ASD-equipped vehicle's actions and the actions of surrounding vehicles.

Table 1. Safety Applications in NYC CVP Deployment

Safety Application	V2V/V2I	Urgency Level	Description
FCW	V2V	Imminent	Helps drivers avoid rear-end crashes
Emergency Electronic Brake Light (EEBL)	V2V	Advisory	Makes drivers aware of suddenly decelerating lead vehicles ahead in the traffic queue
Lane Change Warning (LCW)	V2V	Imminent	Helps drivers avoid lane change crashes
Blind Spot Warning (BSW)	V2V	Advisory	Makes drivers aware of vehicles in their blind spot
Intersection Movement Assist (IMA)	V2V	Imminent	Helps drivers avoid crashes with laterally approaching vehicles at intersections
Speed Compliance (SPDCOMP)	V2I	Advisory	Alerts drivers of appropriate travel speeds at certain locations
Curve Speed Compliance (CSPDCOMP)	V2I	Advisory	Alerts drivers of appropriate travel speeds on curves
Speed Compliance in Work Zone (SPDCOMPWZ)	V2I	Advisory	Alerts drivers of appropriate travel speeds in work zones
Red Light Violation Warning (RLVW)	V2I	Imminent	Helps drivers avoid running red lights at signalized intersections
Oversize Vehicle Compliance (OVCCLEARANCELIMIT)	V2I	Advisory	Alerts drivers of the presence of a low-height bridge or overpass ahead
Emergency Communications and Evacuation Information (EVACINFO)	V2I	Advisory	Communicates to drivers emergency and evacuation information
Pedestrian in Crosswalk Warning (PEDINXWALK)	V2I	Imminent	Helps drivers avoid pedestrian crashes at intersections
Mobile Accessible Pedestrian Signal System (PED-SIG)	I2P (Pedestrian)	Advisory	Provides audible crosswalk signal information to visually-impaired drivers

1.2.3 Deployment Devices and Vehicles

The NYC CVP team deployed 3,000 ASDs on board NYC agency fleet vehicles and 450 RSUs at signalized intersections and other infrastructure locations. Figure 4 presents the distribution of installed ASDs by vehicle type, independent of vehicle gross vehicle weight rating (i.e., light-, medium-, or heavy-duy vehicle) [4].

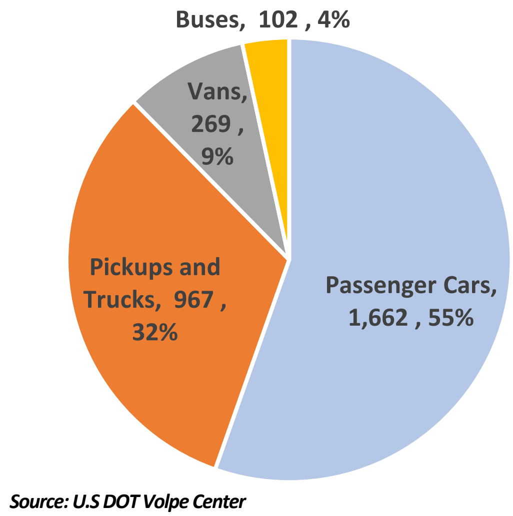


Figure 4. Distribution of Installed ASDs by Vehicle Type

The ASD-equipped vehicles were used by the various NYC agencies for conducting their daily business for the city. Some vehicles were housed in common facilities located across the city and were used by numerous agency staff on an as-needed basis, while some vehicles were assigned to one individual staff member, some of whom might also be authorized to use the vehicle to commute to and from work in addition to conducting their work activities throughout the day. Some vehicles were used as simple transportation from point to point in the city, while others were used in various field inspection, maintenance, and operations for the city's roads, signals, buildings, parks, and other infrastructure.

In terms of how the equipped vehicles were utilized in the CVP site, the NYC CVP team assessed that these vehicles were predominantly focused on the standard business hours on weekdays. However, the 24-7 nature of some of the city agency's activities did extend into the overnight hours and on weekends. The NYC CVP team also observed that these vehicles moved across the city in all five boroughs using all road types, although activities did concentrate on areas of the city which were not predominantly residential.

1.2.4 Experimental Design

The NYC CVP team implemented two experimental designs: *Before and After* design, and *Control and Treatment* design. Both designs included two different functioning states of ASDs:

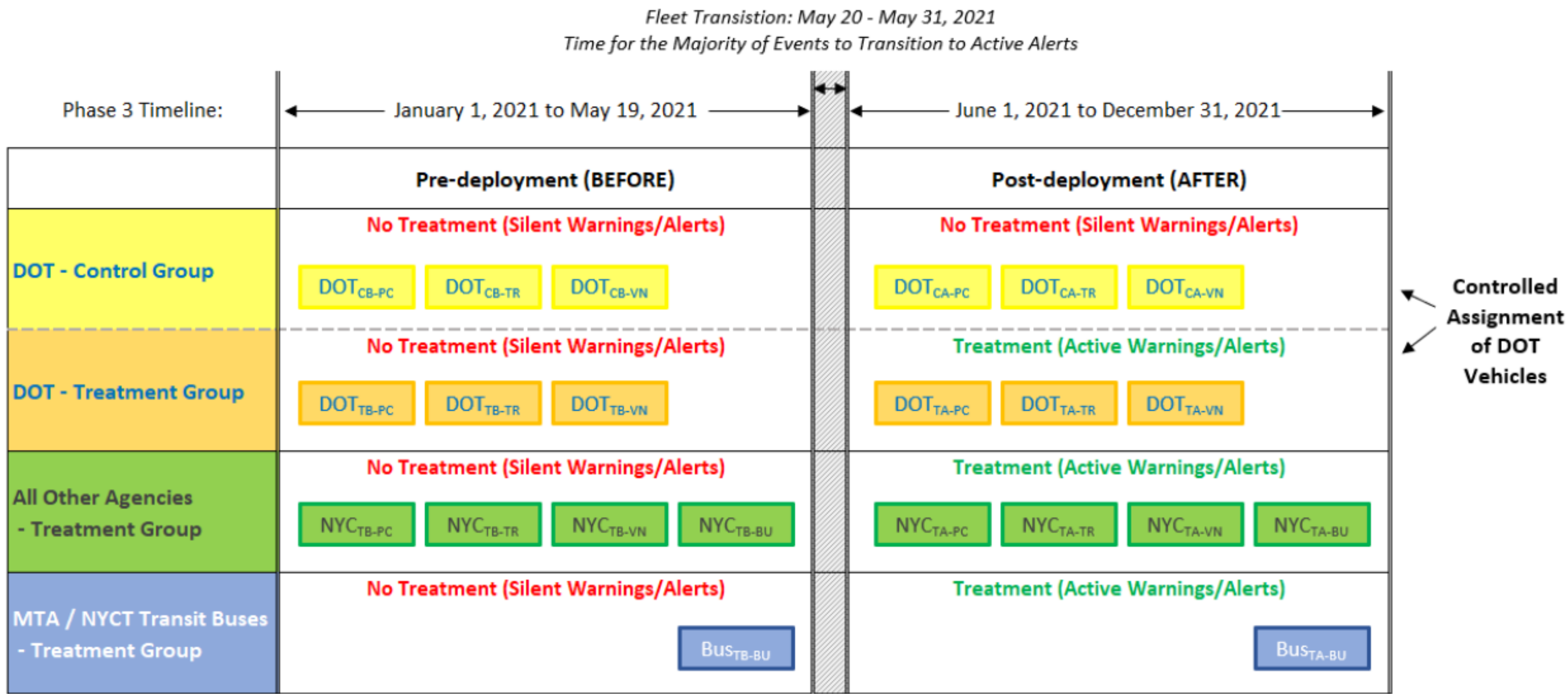
- <u>Silent mode (without CV technology)</u>: system fully deployed and operational but *without* driver notification of ASD perceived warnings.
- <u>Active mode (with CV technology)</u>: system fully deployed and operational but *with* driver notification of ASD perceived warnings.

The *Before* experimental design started with the pre-test or before period when all ASD safety applications operated in the silent mode. CV devices sent and received basic safety messages (BSMs), and their safety applications functioned in the background and did not issue any warnings to drivers. Thus, baseline data were collected during this period. The *After* experimental design involved a systemwide conversion of all ASDs to an active mode in the after period, where warnings generated by the ASDs were now actually issued to the drivers.

The *Control and Treatment* experimental design also included a before period with all CV-equipped vehicles set to silent mode, so as to allow for a pre-test collection of detailed data that were not possible without the installed CV equipment. For the deployment of a post-test control (without) and treatment (with) CV data collection, ASDs were assigned into either the control or treatment group at the beginning of the evaluation period, and they would remain in that group for the entire evaluation period. This experimental design was needed to isolate the impacts of confounding factors that might change throughout the study outside of the control of the NYC CVP team, and might influence the results of the *Before and After* design analyses.

The NYC CVP team planned to have a control group of 150 vehicles or a 5% share of the target ASD-equipped vehicles, in order to allow for a large enough control group to yield more statistically-valid comparisons between the treatment and control groups while still maximizing the size of the treatment group to maximize the potential safety benefits of the CVP deployment. Moreover, the NYC CVP team assigned only NYC DOT vehicles to the control group given the large proportion of the NYC DOT vehicles that were equipped (1,238 or about 41% of all ASD-equipped vehicles), together with the added knowledge about the typical NYC DOT vehicle usage. When selecting a vehicle to the control group, the NYC CVP team selected vehicles that were used as frequently and in a consistent manner as many of the treatment group vehicles.

Figure 5 illustrates the NYC CVP team's experimental design and setting of the ASD mode of operation (silent or active) for the CVP vehicle fleets during the before and after periods of the deployment. NYC DOT vehicles were assigned to either the control or treatment group, while all other vehicles from other agencies were only assigned to treatment groups. For the yearlong deployment, the before period started on January 1, 2021 and ended on May 19, 2021 (about 4.5-month duration). On the other hand, the after period started on May 16, 2021 and ended on December 31, 2021 (about 7.5-month duration).



CB ≡ Control group Before
CA ≡ Control group After
TB ≡ Treatment group Before
TA ≡ Treatment group After

PC ≡ Passenger Cars and SUVs
TR ≡ Pickup and Work Trucks
VN ≡ Vans
BU ≡ Buses (Transit or non-Transit)

Figure 5. NYC CVP Experimental Design by Fleet Vehicle Type

Source: U.S DOT Volpe Center

1.3 Target Crashes

The safety evaluation will address each type of crash that the safety applications are intended to prevent. Each crash type will be addressed separately in the evaluation. Crash types are broken down by the dynamics and movements of the vehicles involved leading up to the impact event, also referred to as "pre-crash scenarios" [5]. Table 2 shows the mapping of NYC safety applications to the following six pre-crash scenario groups:

Table 2. Pre-Crash Scenarios by Safety Application

Safety Application*	Rear End	Lane Change	Crossing Paths	Run Off Road	Pedestrian Crossing	Object
FCW	X					
EEBL	X					
LCW		X				
BSW		X				
IMA			X			
SPDCOMP	X					
CSPDCOMP				X		
SPDCOMPWZ	X			X		
RLVW			X			
OVCCLEARANCELIMIT						X
PEDINXWALK					X	
PED-SIG					X	

*: The EVACINFO application does not address any specific crash type.

- Rear-end crash: a vehicle approaches another vehicle in the same lane ahead, which is traveling in the same direction at slower constant speed, decelerating, or stopped.
- Lane change crash: a vehicle is changing lanes, passing, or merging at a non junction, and then encroaches on another vehicle traveling in the same direction.
- Crossing paths crash: a vehicle approaches an intersection where another vehicle is approaching from a lateral direction. The intersection can be signalized or not signalized, and the vehicles can be approaching either at speed or from a stop.
- Run-off-road crash: a vehicle is going straight or navigating a curve, and then departs the edge of the road without making any other vehicle maneuvers.
- Pedestrian crossing crash: a vehicle is going straight or turning at an intersection, and then approaches a pedestrian who is crossing the street.
- Object crash: a vehicle is moving forward and then strikes a fixed object on the roadway.

1.4 Evaluation Data

The NYC CVP team collected CV-based data from ASDs and RSUs, and non-CV related data.

1.4.1 CV-Based Data

CV-based data include ASD Action Logs that recorded details of movements by the host vehicle (HV) and nearby CV-equipped remote vehicles (RVs), and environment conditions surrounding a CV application warning event. An Action Log was collected in association with a specific event, defined as a condition in which the ASD determined that a warning should be issued to the driver by one of the CV applications. The event data were recorded in the ASD silent and active modes. The ASDs were connected to the vehicle data bus to monitor vehicle dynamics, controls, and signals. This allowed the collection of data about directional signals, braking, steering wheel angle, trajectory, and speed. In addition, ASDs include a 3-axis accelerometer that provides vehicle longitudinal and lateral acceleration data.

Detailed Action Log data were not continuously collected, but instead were only collected whenever an event occurred. Such data include:

- Details regarding the CV application that generated the warning issued, including firmware version and application parameters.
- Content of BSMs transmitted by the HV.
- Content of BSMs received from RVs, within a configurable range of the HV.
- Signal phase and timing (SPaT) message, map data message (MAP), and traveler information message (TIM) received from RSUs within a configurable range of the HV, dependent on the type of warning:
    - RLVW and PEDINXWALK applications collect SPaT messages and MAPs
    - EVACINO and OVCCLEARANCELIMIT applications collect TIMs

Action Logs contain data that were sampled at either 1 or 10 Hz within a time window between 10 and 360 seconds, depending on the safety application as shown in Table 3. In addition to the Action Logs, the HV ASD also recorded a single BSM received from nearby RVs. Of the various individual RV BSMs received by the HV ASD, the BSM from the RV closest in distance to the HV was recorded, along with the corresponding HV ASD's BSM from the same instant. These pairings of BSMs allowed the estimation of the overall number and proximity of the ASD interactions as the CVP progressed through the deployment, irrespective of the number of warning events generated.

Table 3. Action Log Recording Times and Frequency by Safety Application

Safety Application	Pre Warning Record Time (sec)	Post Warning Record Time (sec)	Recording Resolution (Hz)	Alert Category
FCW	7	10	10	Imminent
EEBL	7	10	10	Advisory
IMA	10	10	10	Imminent
BSW	10	10	10	Advisory

LCW	10	10	10	Imminent
SPDCOMP	20	10	1	Advisory
CSPDCOMP	20	10	1	Advisory
SPDCOMPWZ	20	10	1	Advisory
OVCCLEARANCELIMIT	180	180	1	Advisory
RLVW	7	10	10	Imminent
PEDINXWALK	15	15	1	Advisory
EVACINFO	180	180	1	Advisory

1.4.2 Non-CV-Based Data

The following non-CV-based data were available for the evaluation of the CV applications:

- Crash data: NYC Police Department (NYPD) crash database that includes information on crashes where someone is injured or killed, or when there is at least $1000 of damage, as well as all crashes to which the police respond to and complete a report, regardless of roadway or facility type or the type of vehicles involved. The crash reports do not identify if the vehicle is equipped with CV technology or not. Summary-level information of each crash is accessible via both NYPD's TrafficStat program and website and through NYC's Open Data website. While the NYPD crash database is updated daily, the crash types derived from the database are not very detailed and have missing values.
- Weather data: weather station data from the National Weather Service and snowplow data from the PlowNYC system.
- TRANSCOM data: TRANSCOM is a coalition of regional transportation agencies, which provides a common distribution system for transportation information from numerous traffic management centers (TMCs) across the region, including NYC DOT. Two of their data distribution feeds include:
    - Event records: aggregation of notices and advisory statements from TMCs that are updated and published every minute of the day, and can include information on events related to incidents or crashes, various work zone activities, or special events throughout the region that may create atypical demands (e.g., a sporting event) or affect traffic operations (e.g., lane or road closures for parade).
    - Traffic link conditions: published on a one-minute interval basis, describing the average speed and travel time for predefined link segments.

The NYC CVP team fused ASD Action Log and non-CV-based data to tie some details of the operational conditions of the surrounding roadway and environment to the detailed records of the ASD Action Log. Such data fusion can help provide some context of the operating conditions in which the CV application warning was issued to the driver, by accounting for the confounding factors on the evaluation of safety applications and changes in vehicle/driver responses under different conditions.

1.4.3 ASD Action Log Data Obfuscation Procedures

The NYC CVP team obfuscated vehicle, time, and location data from the ASD Action Logs prior to data upload to the Secure Data Commons (SDC) (see Section 1.5 for SDC description):

- Vehicle and CV message ID number: the HV's ASD serial number, as part of the header of the event record format, was removed. The following vehicle-specific data elements in the Action Log were retained:
    - Temporary or pseudo IDs periodically generated by the ASD and included in the BSM
    - Vehicle type information
    - HV's ASD firmware version
    - HV's ASD parameter settings
- Time and date: precise time of the event record was removed and replaced with two-letter code to represent the time of day when the event occurred:
    - Overnight period (12:00 am – 6:00 am): NT
    - Morning Peak (6:00 am – 10:00 am): AM
    - Midday Period (10:00 am – 3:00 pm): MD
    - Afternoon Peak (3:00 pm – 8:00 pm): PM
    - Evening Period (8:00 pm – 12:00 am): EV
- Location: any detailed latitude, longitude, and elevation data recorded in any of the CV messages contained in the Action Logs were removed and replaced with a cartesian coordinate system in the stored obfuscated records to create vehicle trajectory information. The obfuscation of location data was done independently for each event Action Log data, and the new reference point for the entire data record was the location of the HV at the instant the CV warning is issued (X=Y=Z= 0 meter). Information about where in the city and on what type of roadway the event occurred was classified into two separate types of location bins to help provide additional context to the Action Log detailed records:
    1. Manhattan's equipped roadways
        - 1-way avenues
        - 2-way avenues
        - 1-way cross streets
        - 2-way cross streets
        - Freeways/parkways/ramps
    2. Brooklyn's all equipped roadways

1.4.4 Secure Data Commons

The SDC is a cloud-based data analytics platform that was built by the ITS JPO to support the CVP program. The platform was designed to maintain the security of the CVP data, while still allowing access to those who needed it (i.e., CVP teams and evaluators). The platform was also equipped with the analytical tools that the evaluators would need to conduct the evaluation. All NYC CVP site-generated data that were used for the evaluation were uploaded directly to the SDC, and the evaluators conducted their analyses completely within this environment.

2 Safety Impact Assessment Approach

This section presents the objectives, technical approach, and scope of the safety evaluation.

2.1 Objectives

The Volpe team pursued the following objectives to independently evaluate the safety impact of the NYC CVP safety applications:

1. Assess the performance capability of the CVP safety applications by characterizing the efficacy of the alerts in terms of valid (true-positive) and invalid (false-positive) alerts.
2. Evaluate changes in vehicle/driver response to advisory alerts for benign driving situations and crash-imminent warnings for driving conflicts (Table 1), between silent (unassisted) and active (assisted) alerts issued by the CVP safety applications. Driving conflicts refer to high-risk, near-crash scenarios where a driver had to intervene to avoid a crash.

2.2 Technical Approach

The Volpe team applied the technical approach shown in Figure 6 for its safety impact assessment of each of the NYC CVP safety applications, which was adapted from the safety impact assessment of the Tampa CVP safety applications [1]. This approach consists of the following six steps:

1. Filter alert events that contained issues with the data that the NYC CVP team collected, processed, and uploaded to the SDC. This initial step is critical to ensure that the safety impact analysis in the following five steps is conducted on alert events with good data.
2. Assess the validity of safety application alerts in events with good data. This step addresses the performance capability of the NYC CVP safety applications, which meets the first objective of the independent safety evaluation. This is another filtering step that identifies events with valid (true positive) alerts for further analysis in the following four steps, and excludes events with invalid (false positive) alerts from further assessment.
3. Break down the events with valid alerts by treatment and control groups, before and after deployment periods, and silent and active alerts. This step is essential for the three following steps that address vehicle/driver response to valid alerts under similar initial conditions and the safety effectiveness of the NYC CVP safety applications.
4. Identify the initial conditions of events with valid alerts at alert onset, generate descriptive statistics of their measures of performance by alert status, and conduct statistical tests to assess any similarity of these initial conditions between two experimental groups. This step is necessary to ensure the similarity of kinematic conditions at alert onset between two experimental groups, prior to conducting the comparison of vehicle/driver response to valid alerts between these two groups in the following step.
5. Identify vehicle/driver response measures after alert onset, generate descriptive statistics of these measures of performance by alert status, and conduct statistical tests to reveal any statistically-significant differences in any of these measures between two experimental groups. This step meets the second objective of the independent safety evaluation.
6. Assess the effectiveness of the safety applications in improving the various measures of

performance for vehicle/driver response to alerts, based on statistically-significant differences between assisted drivers in events with active alerts and unassisted drivers in events with silent alerts.

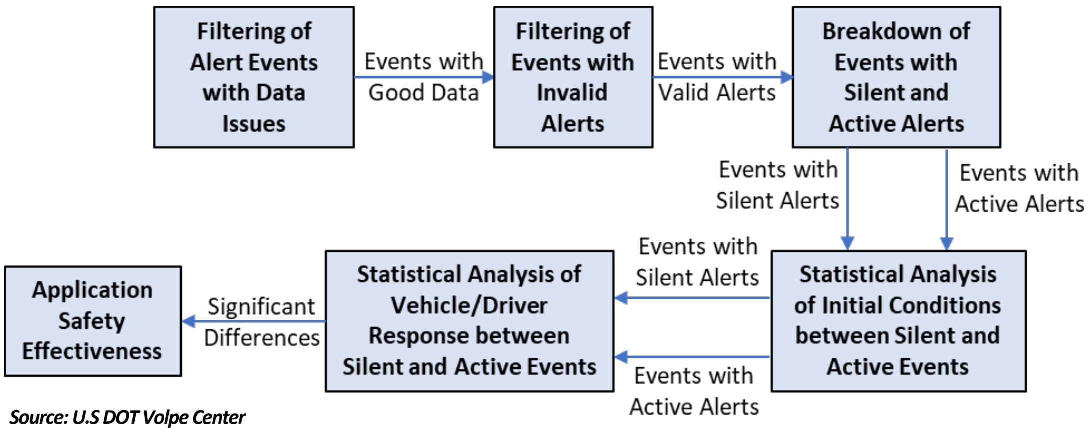


Figure 6. Safety Impact Assessment Approach

2.3 Scope

The scope of the safety impact analysis addresses the statistical comparisons among different experimental groups, safety applications, and driving conflicts and exposure.

2.3.1 Statistical Comparisons

The NYC CVP experimental design includes a treatment group and a control group of vehicles, as illustrated in Figure 5. The event Action Logs allow the distinction between the vehicles in the control group and the treatment group, as well as between events with silent and active alerts during recorded events. Obfuscated logged time and date of the events, such as 2019-11-THU-AM (Section 1.4.3), identify the month when an event occurred but not the day of the month. The before period started on January 1, 2021 and ended on May 19, 2021, while the after period started on May 20, 2021 and ended on December 31, 2021 (Section 1.2.4). Since the before period ended in the middle of May, the NYC CVP date information did not allow for the distinction between the end of the before period and the start of the after period for alert events in May. This distinction was particularly problematic for the control group since all its alert events were silent in May and during the yearlong deployment. Consequently, the Volpe team considered all alert events encountered by the control group in May as part of the before period. In contrast, this distinction could be made for the treatment group by assigning events with silent alerts to the before period and events with active alerts to the after period occurring in May.

Based on sample size, the Volpe team performed one, some, or all of the following comparisons between the experimental groups:

1. Analysis of control and treatment groups in the before period, which compared vehicle/driver response to silent alerts from all treatment vehicles to vehicle/driver response to silent alerts from all control vehicles in the before period. This analysis evaluated the similarity in

performance between these two groups in the before period when all vehicles received silent alerts.

2. Analysis of the treatment group, which compared vehicle/driver response to silent alerts in the before period to vehicle/driver response to active alerts in the after period from all treatment vehicles. This analysis assessed any change in vehicle/driver performance by the treatment group as a result of active alerts by the safety applications.
3. Analysis of the control group, which compared vehicle/driver response to silent alerts from all control vehicles between the before and after periods. This analysis assessed any change in vehicle/driver performance by the control group due to some confounding factors.
4. Analysis by alert status, independent of control or treatment groups and before or after deployment periods, which compared vehicle/driver response between events with silent alerts and events with active alerts. This analysis would have the largest sample sizes among the four comparison options. It would also be appropriate to conduct such analysis since different drivers might have alternated in driving the same deployment vehicles in some instances.

The treatment group experienced 83 events with active alerts in the before period and 6,978 events with silent alerts in the after period (Section 3.1.1). This result suggests some errors in data collection because the treatment group was designed to receive only silent alerts in the before period and only active alerts in the after period. Consequently, the Volpe team excluded from the comparison analysis of the treatment group all events with active alerts from January through April and all events with silent alerts from June through December. Events with silent and active alerts in May were considered as part of the before and after periods, respectively.

The Volpe team performed any of the four comparison analyses given sufficient data (sample size) for each safety application.

2.3.2 Safety Applications

The Volpe team analyzed ten of the thirteen NYC CVP safety applications listed in Table 1, excluding the following three applications:

1. ***EVACINFO***: transmits information from the NYC Office of Emergency Management and from the NYC DOT Office of Emergency Response to CVs near or within affected areas during incidents. This application notifies drivers if they are within the designated warning zone, which may or may not be in the direct path of their planned travel and may elicit different driver responses that are hard to quantify from available data (i.e., continue on or alter their intended path of travel).
2. ***OVCCLEARANCELIMIT***: advises the driver of a potential crash before the bridge, overpass, or tunnel to allow the vehicle with long height to exit the restricted roadway and find an alternate route; and warns the driver of an impending crash before the over-height bridge, overpass, or tunnel to stop the vehicle completely and avoid the crash. The latter warning function has an immediate impact on driving safety. Unfortunately, the event Action Log does not distinguish between advisory and warning messages. Based on SDC data, this application issued a total of 1,487 alerts during the yearlong deployment. About 94% of these alerts (1,390) were received by passenger vehicles and light trucks, pickups, or vans that should be safe to travel under a low

bridge. The remaining 6% of these alerts were issued to medium/heavy trucks with various axle types (94) and transit buses (3). Since the participants in the NYC CVP are very familiar with NYC roadways, it is likely that most of these alerts are of advisory nature.

3. *PED-SIG*: provides advisory, audible crosswalk signal information to visually-impaired drivers. The Volpe team has access to only aggregated data for performance measures selected by the NYC CVP team. The NYC CVP team performed the evaluation of this application [4].

2.3.3 Driving Conflicts and Exposure

Since the NYC CVP data were not collected continuously during the deployment, the Volpe team associated the encounter with driving conflicts only with recorded events that triggered valid alerts (Step 2 of the safety impact assessment approach). As a result, the Volpe team was not able to account in the analysis for encountered driving conflicts that did not trigger any alert from the NYC CVP safety applications.

Exposure information was only available from ASD interactions with other ASDs. Exposure data can be gleaned only from first message and last message for each V2V encounter; thus, one cannot determine relative location of the vehicles and the type of driving conflict, such as the HV following the RV for FCW-related scenarios or the HV traveling side-by-side of the RV for LCW/BSW-related scenarios. As for ASD interactions with RSUs, one cannot determine from available NYC CVP data the exposure of ASDs to RSUs where V2I applications are enabled. Moreover, exposure analysis for control and treatment vehicles cannot be performed due to the inability of distinguishing among the vehicle groups (i.e., between NYC DOT and Other Agencies vehicles, and between control and treatment vehicles). Consequently, the Volpe team was unable to perform any analysis about vehicle exposure to driving conflicts.

3 NYC CVP Observations

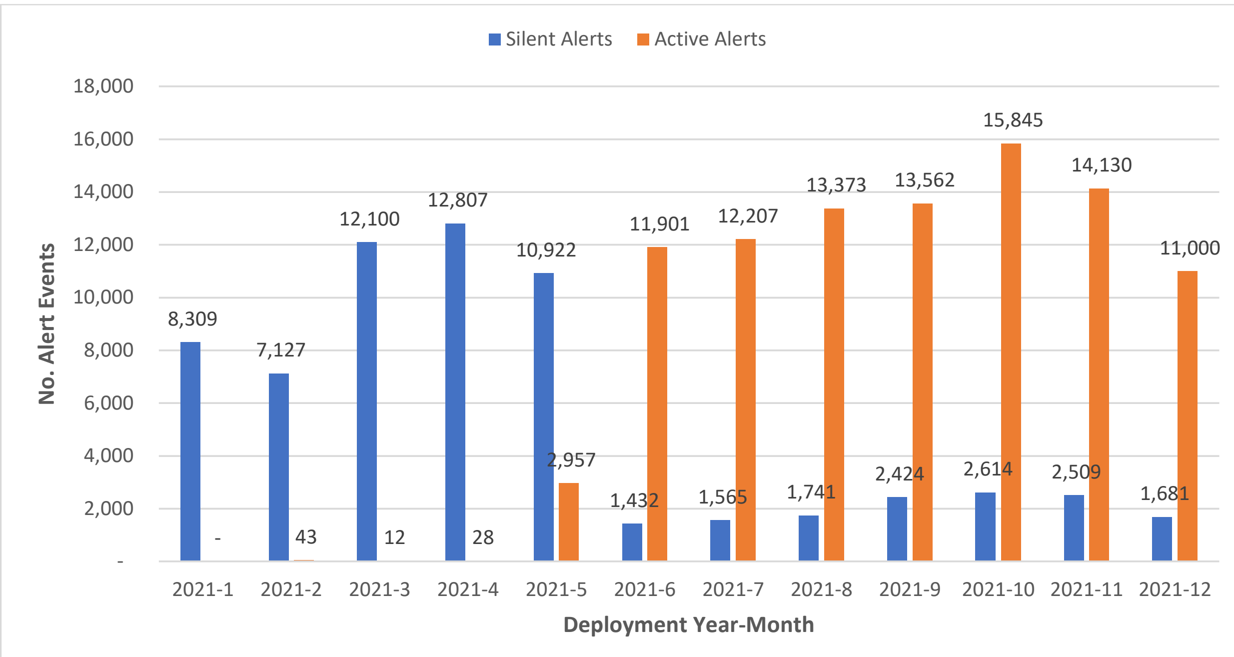
This section provides the counts of observed events with silent and active alerts:

- By all, V2I, and V2V safety applications;
- During the yearlong, before, and after deployment periods; and
- For all, treatment, and silent groups of vehicles.

In addition, this section presents the NYC CVP team's filtering of events due to data issues.

3.1 Observed Alert Events during Deployment

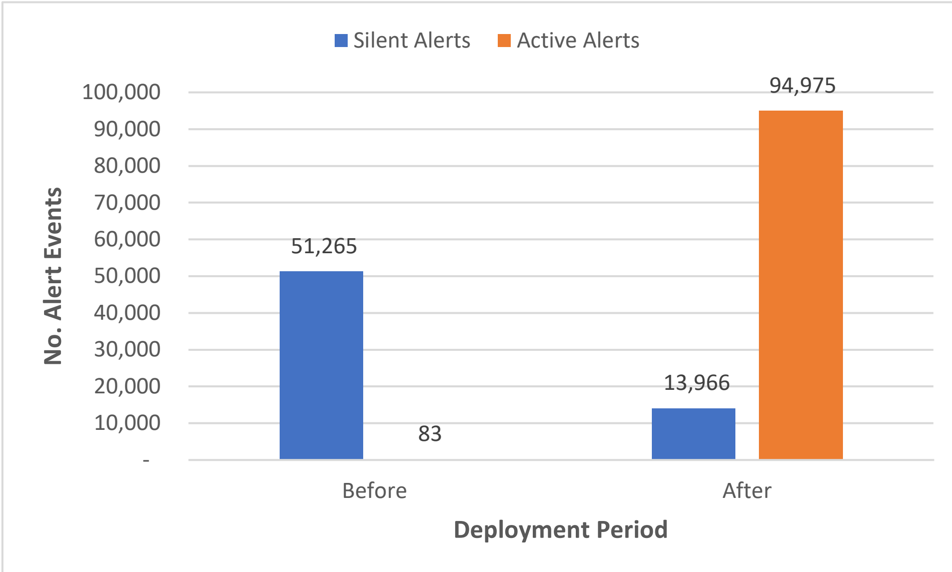
The treatment and control groups experienced a total of 160,289 alert events during the NYC CVP yearlong deployment. These events comprised 65,231 events with silent alerts (41%) and 95,058 events with active alerts (59%). Figure 7 illustrates the breakdown of silent and active alert events by month during the yearlong deployment.



Source: U.S DOT Volpe Center

Figure 7. Distribution of All Group Events by Alert Status and Deployment Year and Month

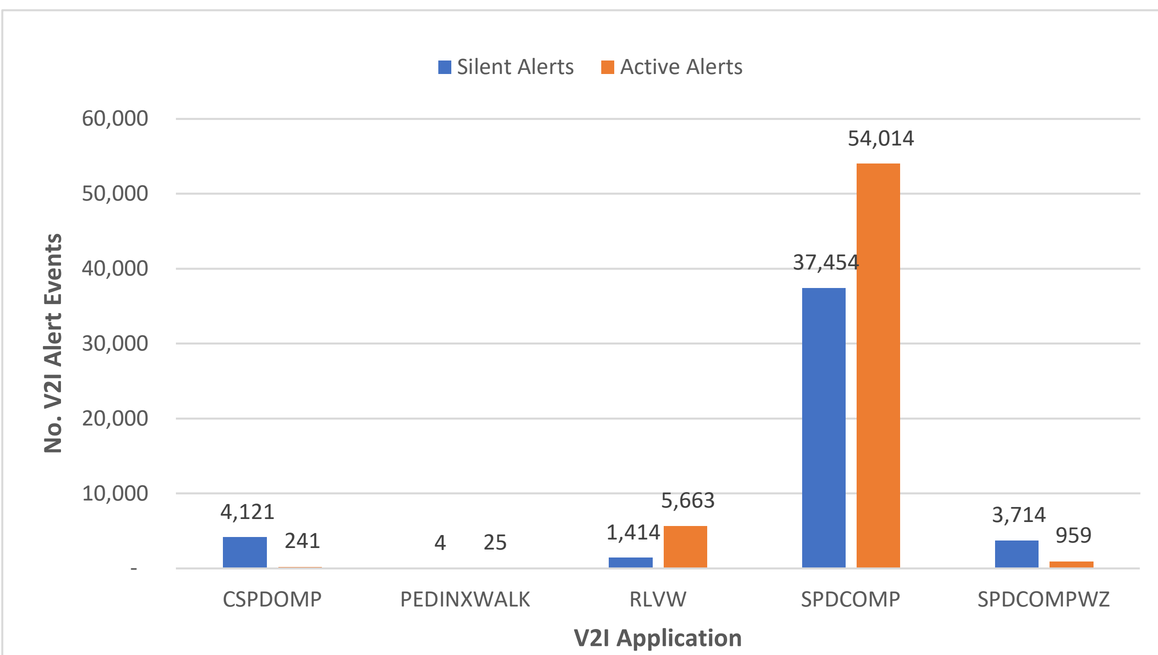
The treatment and control groups experienced 51,348 alert events in the before period (32%) and 108,941 alert events in the after period (68%). Figure 8 breaks down the silent and active alert events by the before and after periods.



Source: U.S DOT Volpe Center

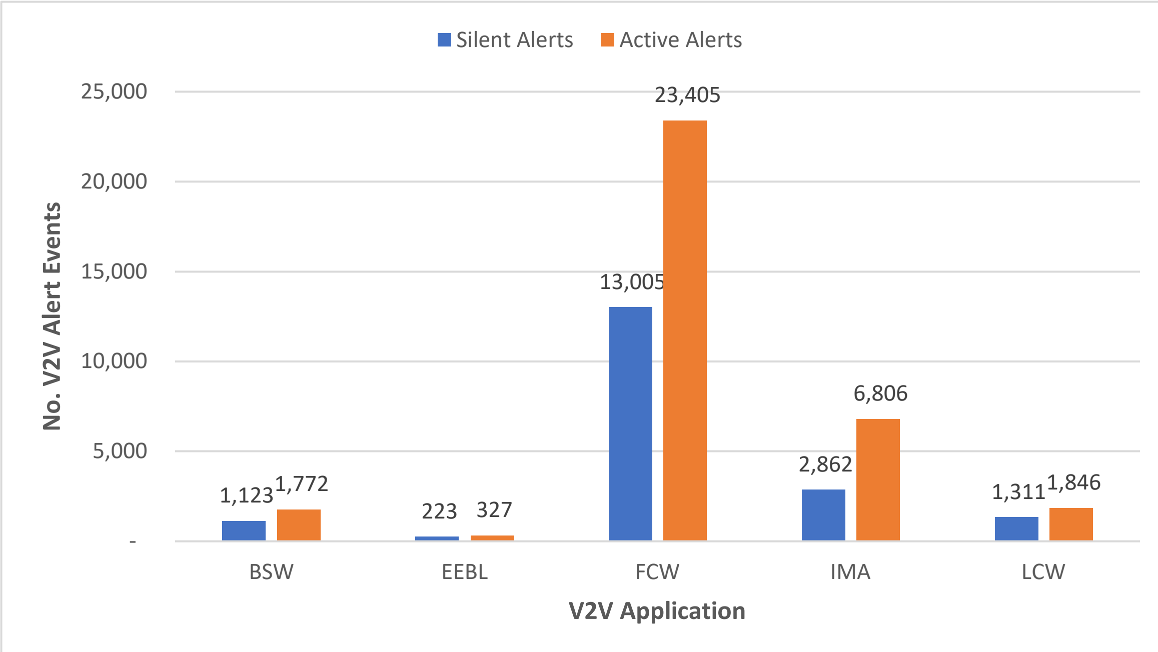
Figure 8. Breakdown of All Group Events by Alert Status and Deployment Period

The two experimental groups encountered 107,609 V2I alert events (67%) and 52,680 V2V alert events (33%). V2I events comprised 46,707 events with silent alerts (43%) and 60,902 events with active alerts (57%). On the other hand, V2V events comprised 18,524 events with silent alerts (35%) and 34,156 events with active alerts (65%). Figure 9 and Figure 10 illustrate the breakdown of silent and active alert events by month during the yearlong deployment respectively for V2I and V2V applications. It is noteworthy that the V2I PEDINXWALK application only issued a total of 29 alerts during the yearlong deployment.



Source: U.S DOT Volpe Center

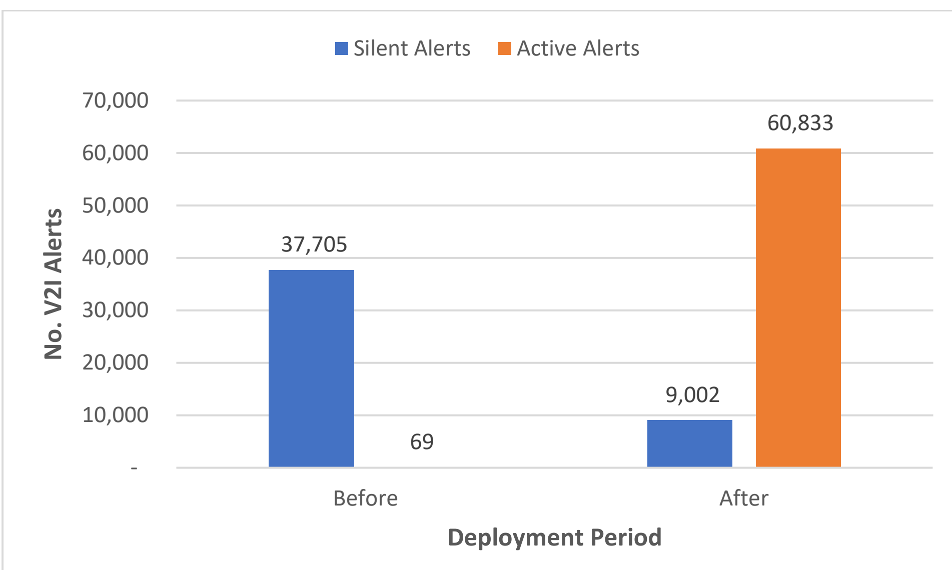
Figure 9. Distribution of All V2I Alert Events by Alert Status and Deployment Year and Month



Source: U.S DOT Volpe Center

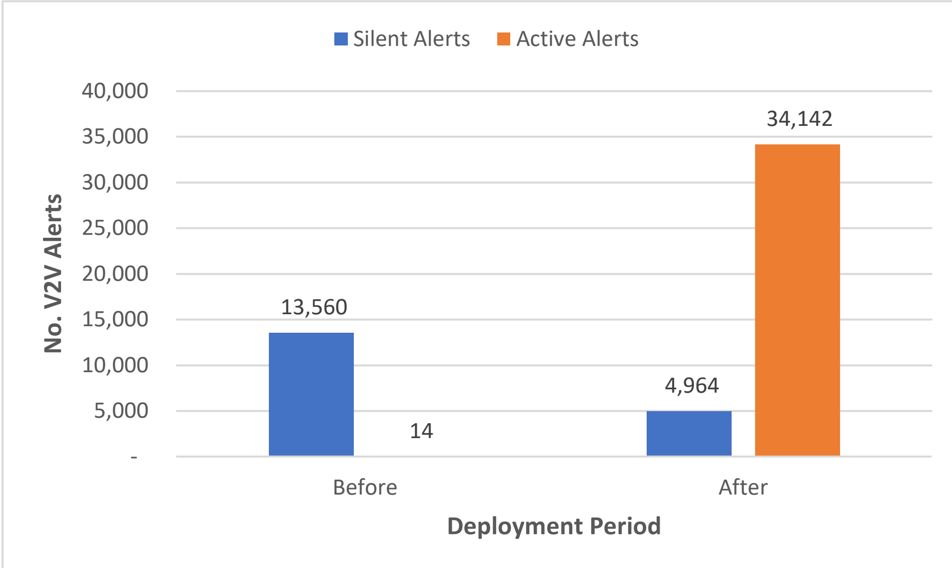
Figure 10. Distribution of All V2V Alert Events by Alert Status and Deployment Year and Month

The two experimental groups experienced 37,774 V2I alert events in the before period (35%) and 69,835 V2I alert events in the after period (65%). In contrast, 13,574 V2V alert events happened in the before period (26%) and 39,106 of such events occurred in the after period (74%). Figure 11 and Figure 12 break down the silent and active alert events by the before and after periods for V2I and V2V applications, respectively.



Source: U.S DOT Volpe Center

Figure 11. Breakdown of All Group V2I Alert Events by Alert Status and Deployment Period

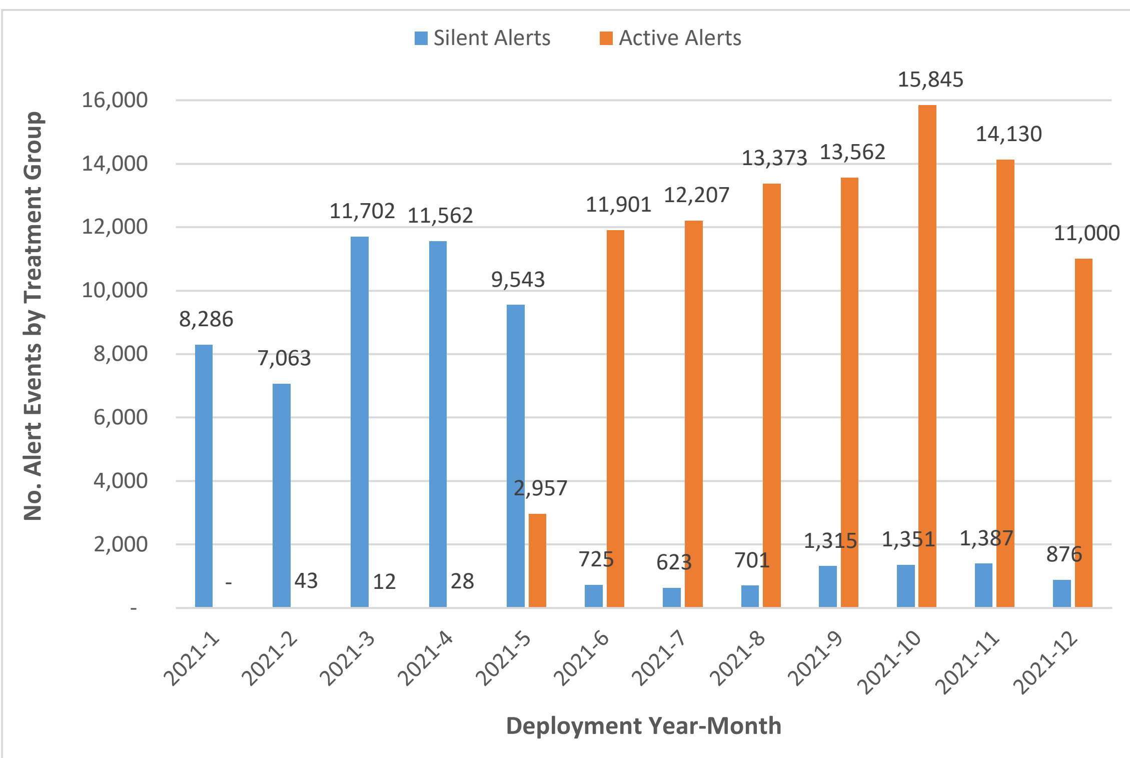


Source: U.S DOT Volpe Center

Figure 12. Breakdown of All Group V2V Alert Events by Alert Status and Deployment Period

3.1.1 Observed Alert Events by Treatment Group

The treatment group experienced a total of 150,192 alert events during the NYC CVP yearlong deployment. These events comprised 55,134 events with silent alerts (37%) and 95,058 events with active alerts (63%). Figure 13 illustrates the breakdown of silent and active alert events by month during the yearlong deployment.

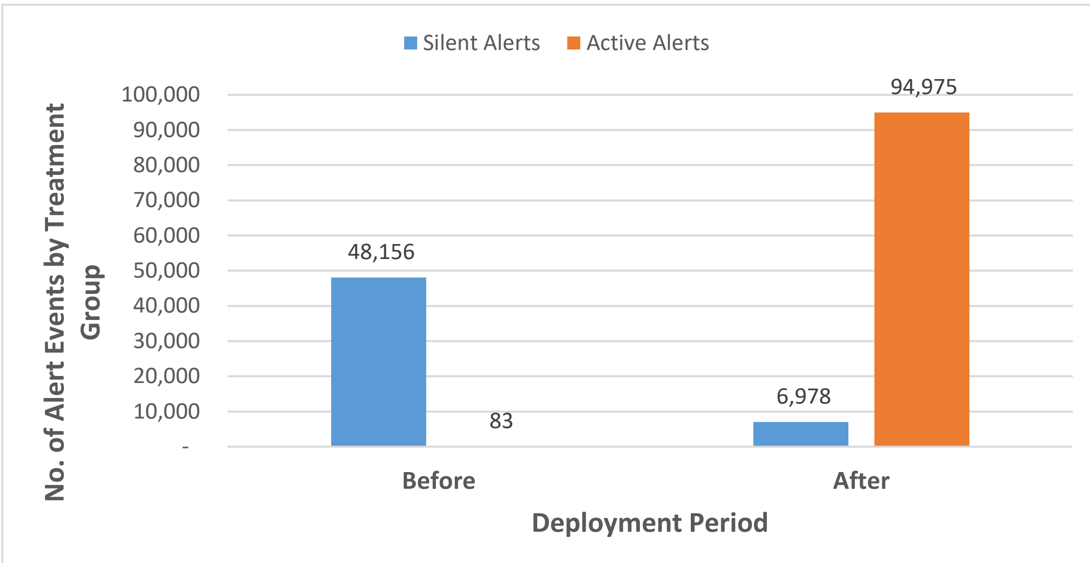


Source: U.S DOT Volpe Center

Figure 13. Distribution of Treatment Group Events by Alert Status and Deployment Year and Month

The before period contained 48,239 treatment group alert events (32%). The after period contained 101,953 treatment group alert events (68%). Figure 14 breaks down the silent and active alert events by the before and after periods. By design, the treatment group should not have received 83 active alerts in the before period and 6,978 silent alerts in the after period.

The treatment group experienced 100,942 V2I alert events (67%) and 49,250 V2V alert events (33%). The next two subsections present detailed information about observed alert events respectively for V2I and V2V applications.

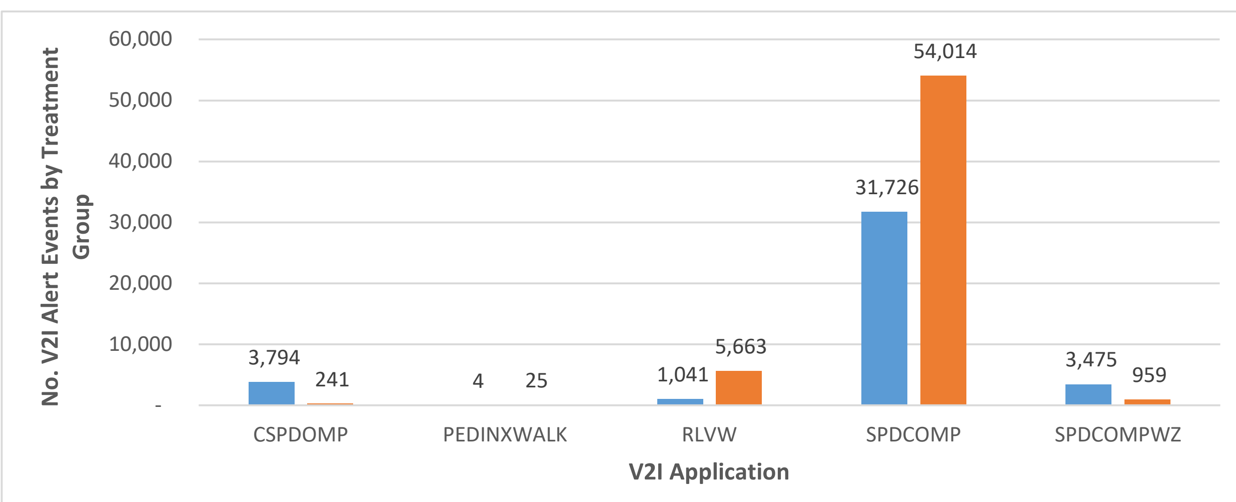


Source: U.S DOT Volpe Center

Figure 14. Breakdown of Treatment Group Events by Alert Status and Deployment Period

3.1.1.1 Observed V2I Alert Events by Treatment Group

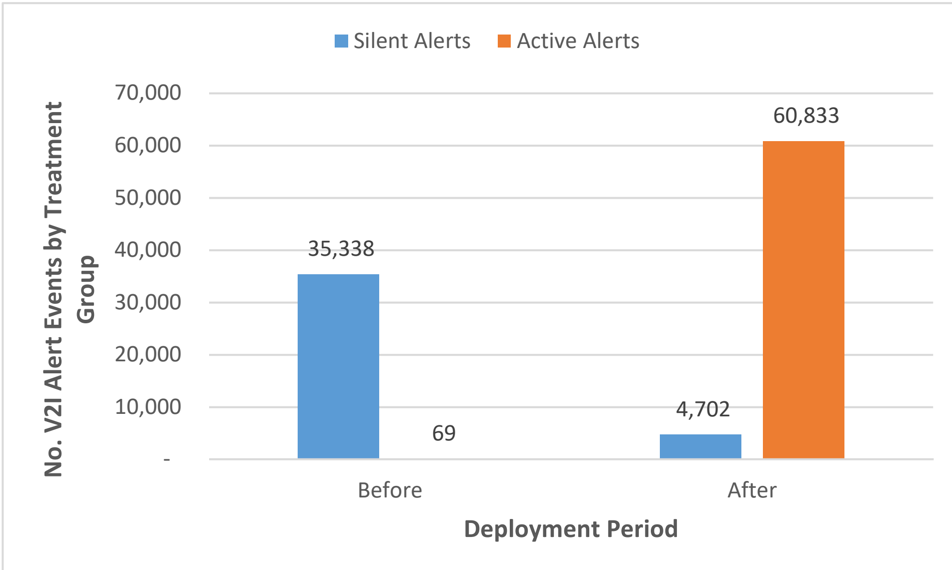
The treatment group experienced 40,040 V2I events with silent alerts (40%) and 60,902 V2I events with active alerts (60%) during the NYC CVP yearlong deployment. Figure 15 illustrates the breakdown of these silent and active alert events by application and month during the yearlong deployment.



Source: U.S DOT Volpe Center

Figure 15. Distribution of Treatment Group Events by V2I Application and Alert Status

The before period contained 35,407 treatment group V2I alert events (35%). The after period contained 65,535 treatment group V2I alert events (65%). Figure 16 breaks down the silent and active V2I alert events by the before and after periods. By design, the treatment group should not have received 83 V2I active alerts in the before period and 6,978 V2I silent alerts in the after period.

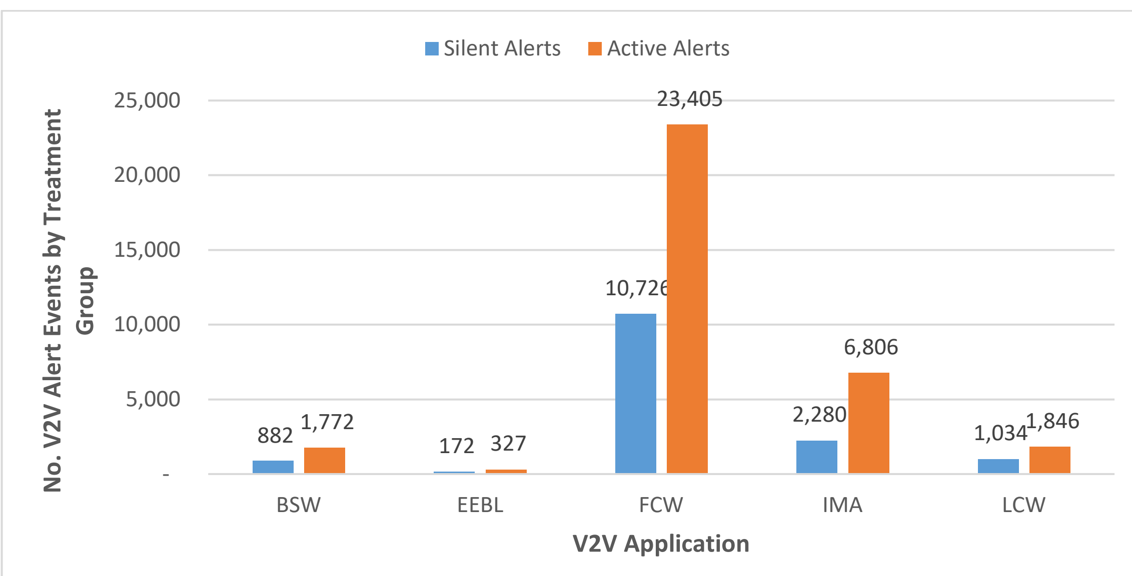


Source: U.S DOT Volpe Center

Figure 16. Breakdown of Treatment Group V2I Alert Events by Alert Status and Deployment Period

3.1.1.2 Observed V2V Alert Events by Treatment Group

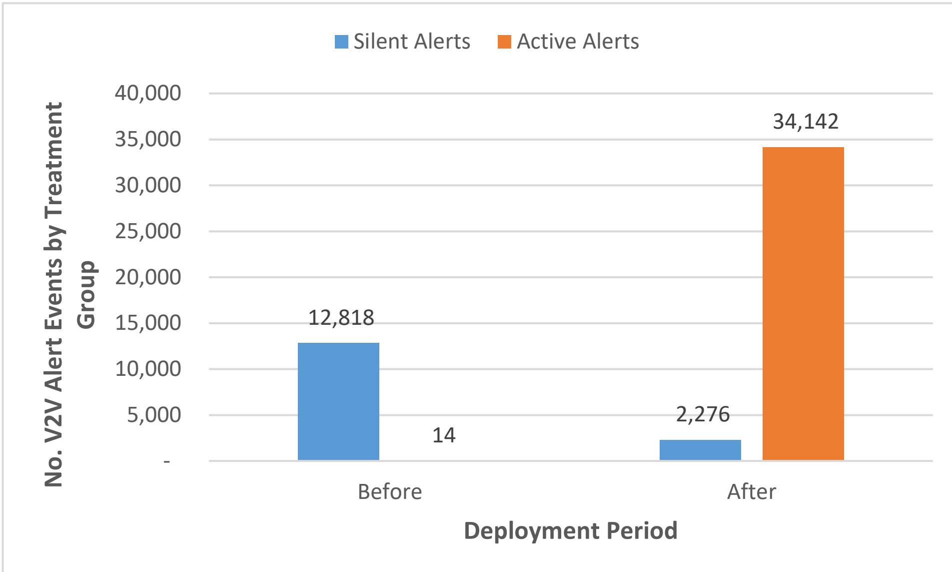
The treatment group experienced 15,094 V2V events with silent alerts (31%) and 34,156 V2V events with active alerts (69%) during the NYC CVP yearlong deployment. Figure 17 illustrates the breakdown of V2V silent and active alert events by application and month during the yearlong deployment.



Source: U.S DOT Volpe Center

Figure 17. Distribution of Treatment Group Events by V2V Application and Alert Status

The before period contained 12,832 treatment group V2V alert events (26%). The after period contained 36,418 treatment group V2V alert events (74%). Figure 18 breaks down the silent and active V2V alert events by the before and after periods. By design, the treatment group should not have received 14 V2V active alerts in the before period and 2,276 V2V silent alerts in the after period.

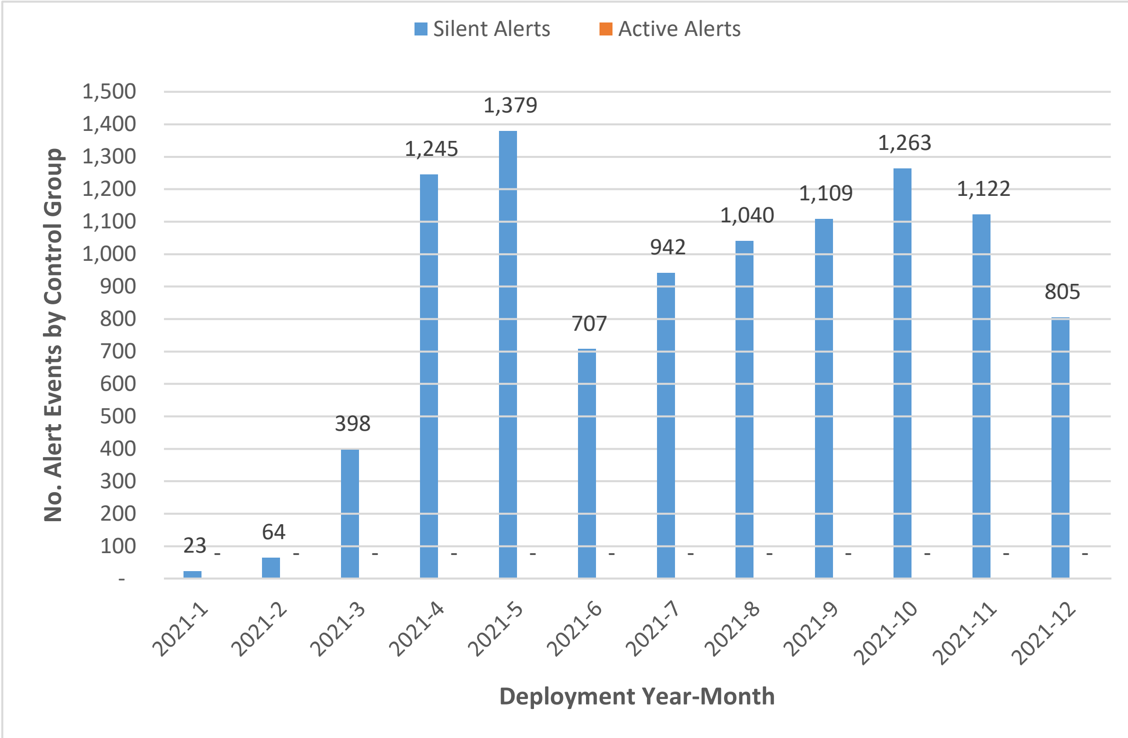


Source: U.S DOT Volpe Center

Figure 18. Breakdown of Treatment Group V2V Alert Events by Alert Status and Deployment Period

3.1.2 Observed Alert Events by Control Group

The control group experienced a total of 10,097 alert events during the NYC CVP yearlong deployment. All these events received silent alerts. Figure 19 illustrates the breakdown of silent alert events by month during the yearlong deployment.



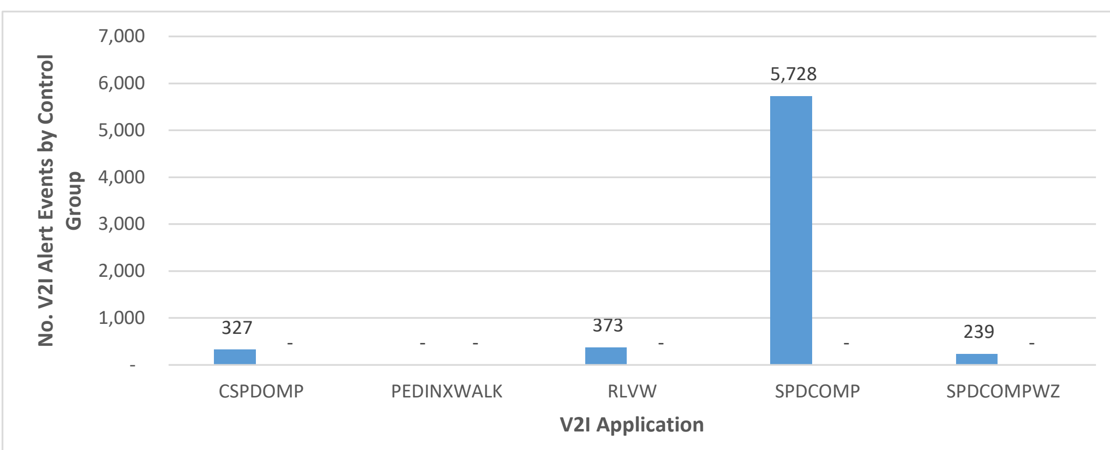
Source: U.S DOT Volpe Center

Figure 19. Distribution of Control Group Events by Alert Status and Deployment Year and Month

A total of 3,109 control group alert events occurred in the before period (31%), and 6,988 of such events occurred in the after period (69%). The control group experienced 6,667 V2I alert events (66%) and 3,430 V2V alert events (34%). The next two subsections present detailed information about observed alert events by the control group respectively for V2I and V2V applications.

3.1.2.1 Observed V2I Alert Events by Control Group

The control group experienced all 6,667 V2I events with silent alerts (100%) during the NYC CVP yearlong deployment. Figure 20 illustrates the breakdown of these silent alert events by month during the yearlong deployment.



Source: U.S DOT Volpe Center

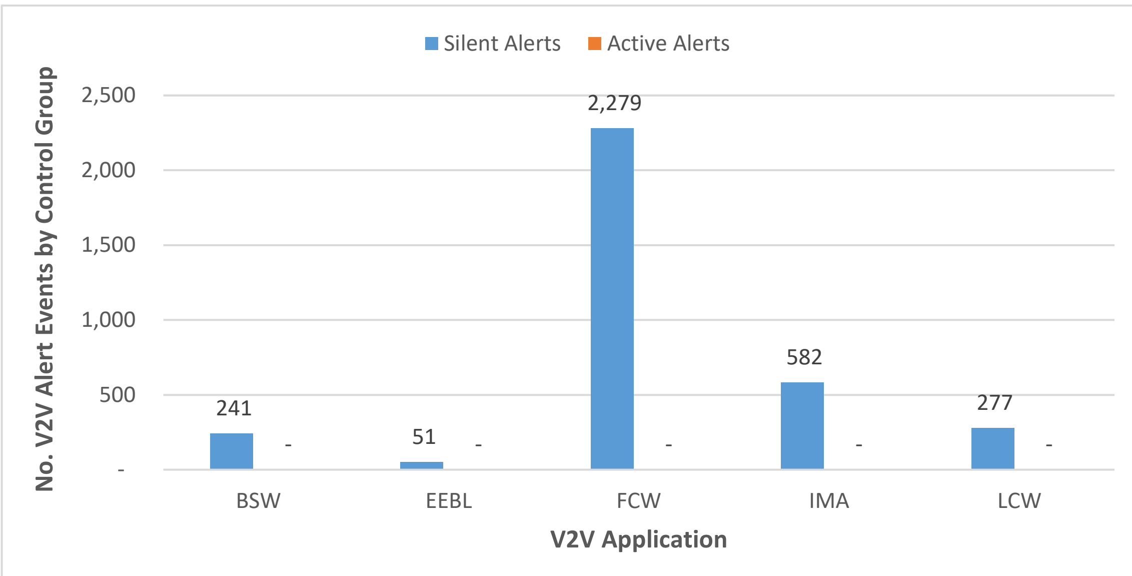
Figure 20. Distribution of Control Group Events by V2I Application and Alert Status

The before period contained 2,367 control group V2I alert events (36%). The after period contained 4,300 control group V2I alert events (64%).

As seen in Figure 20, the control group did not experience any PEDINXWALK events during the yearlong deployment. Figure 20 shows that the treatment group encountered 4 PEDINXWALK events with silent alerts and 25 such events with active alerts. As a result, the Volpe team did not analyze this V2I safety application due to the lack of sufficient number of events.

3.1.2.2 Observed V2V Alert Events by Control Group

The control group experienced all 3,430 V2V events with silent alerts (100%) during the NYC CVP yearlong deployment. Figure 21 illustrates the breakdown of these silent alert events by month during the yearlong deployment.



Source: U.S DOT Volpe Center

Figure 21. Distribution of Control Group Events by V2V Application and Alert Status

The control group encountered 742 V2V alert events in the before period (22%) and 2,688 V2V alert events in the after period (78%).

3.2 Filtering of Alert Events with Data Issues

The NYC CVP team observed some anomalies in the data while analyzing alert events for their own evaluation report that was completed in December 2021 [4]. To remedy such data anomalies, the NYC CVP team removed events with the following criteria:

1. Incorrect triggering locations, keeping events that were triggered near the spatial locations that were instrumented with the corresponding V2I applications. For example, events that did not display a curvature in their trajectories were removed for CSPDCOMP applications. All SPDCOMPWZ events occurring in boroughs that did not contain any instrumented locations were removed.
2. Incorrect pre-warning and post-warning record times, considering events with record times longer than the preset record time (Table 3) to be erroneous and removing them before subsequent analysis. A one second buffer was added to the preset record time to account for

potential measurement errors. The Volpe team analyzed already-processed data by the NYC CVP team as well as the SDC team, and did not have access to actual collected data (e.g., BSMs). Thus, the Volpe team applied this filter following the NYC CVP team.

3. Observed speed values greater than 26.8 m/s (60 mph), based on NYC CVP team's observed speed values after applying the first two steps above. The Volpe team decided to use the threshold of 24.6 m/s (55 mph), considering travel speeds in NYC with congested traffic.
4. Warnings triggered above the speed limit threshold, considering three configuration parameters *excessiveSpd* for SPDCOMP, *excessiveCurveSpd* for CSPDCOMP, and *excessiveZoneSpd* for SPDCOMPWZ that represent the excessive speed or threshold above the posted (for SPDCOMP) or advisory (for CSPDCOMP and SPDCOMPWZ) speed limit for determining whether or not a vehicle's speed violates that speed limit. According to the NYC CVPD implementation of SPDCOMP, CSPDCOMP, and SPDCOMPWZ, warnings were to be triggered when the speed of a CV reached the established speed limit, meaning the excessive speed parameters were to be set to zero. Thus, events with warnings triggered with incorrectly set non-zero excessive speed limit thresholds were removed.
5. If the trajectory of the HV and RV was discontinuous or unreasonable.
6. If recorded speed values for an event were partially zero but its trajectory showed the vehicle was moving. The NYC CVP team recalculated speed values based on GPS coordinates if recorded speed values for an event were all zero but its trajectory showed the vehicle was moving. The Volpe team could not do such recalculation since GPS coordinates were not available to them.
7. If recorded speed values for an event were equal to a non-zero constant but its trajectory showed inconstant movement. The NYC CVP team recalculated speed values based on GPS coordinates if (calculated speed value) / (recorded speed value) was not clustered around 1. The Volpe team could not do such recalculation since GPS coordinates were not available to them.

The NYC CVP team removed from 12% to 28% of the data for V2I applications, excluding the CSPDCOMP application that included a relatively large proportion of events removed with incorrect triggering locations from an early TIM message creating false (but silent) alerts in the before period [4]. The Volpe team applied NYC CVP team's filters, where possible or with modification, in addition to their own filters for dealing with data issues as discussed in the following section.

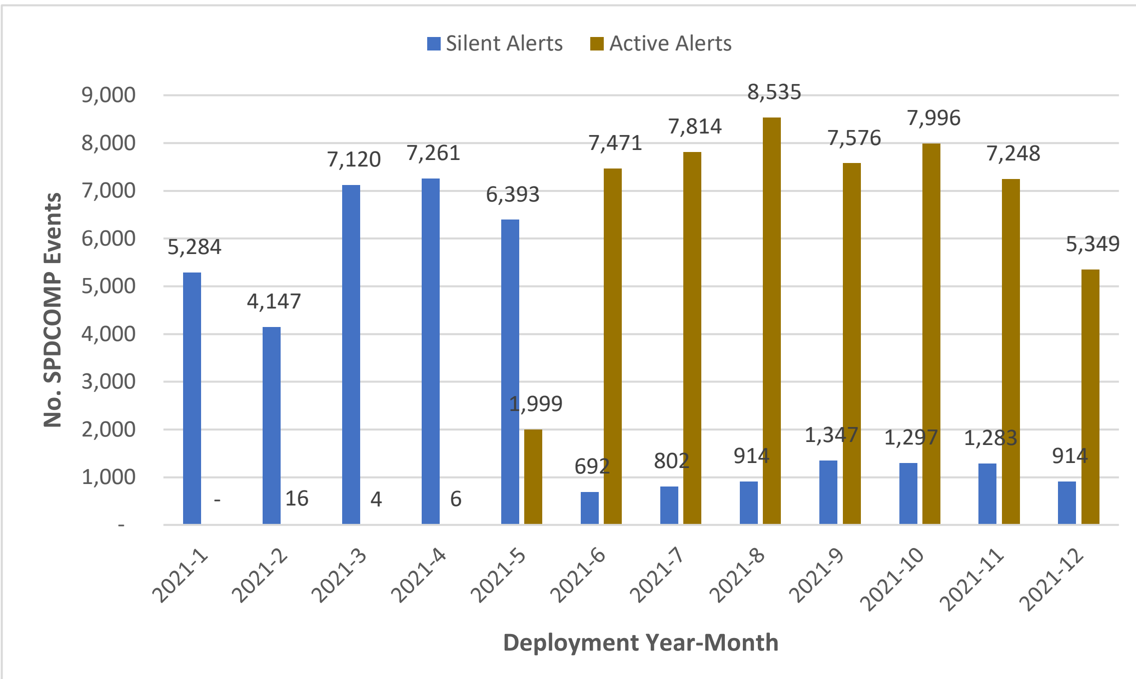
4 Analysis of V2I Alert Events and Vehicle/Driver Response

This section presents the results of applying the steps of the safety impact assessment approach to each of the following four V2I safety applications: SPDCOMP, RLVW, CSPDCOMP, and SPDCOMPWZ.

4.1 Speed Compliance Warning

4.1.1 Observed SPDCOMP Events

The SDC contained 91,468 SPDCOMP events from the NYC CVP deployment. These events comprised 37,454 silent SPDCOMP events (41%) and 54,014 active SPDCOMP events (59%). Figure 22 illustrates the breakdown of silent and active speed compliance events by month during the yearlong deployment. In the before period, there were 30,231 SPDCOMP events (33%). In the after period, there were 61,237 SPDCOMP events (67%).

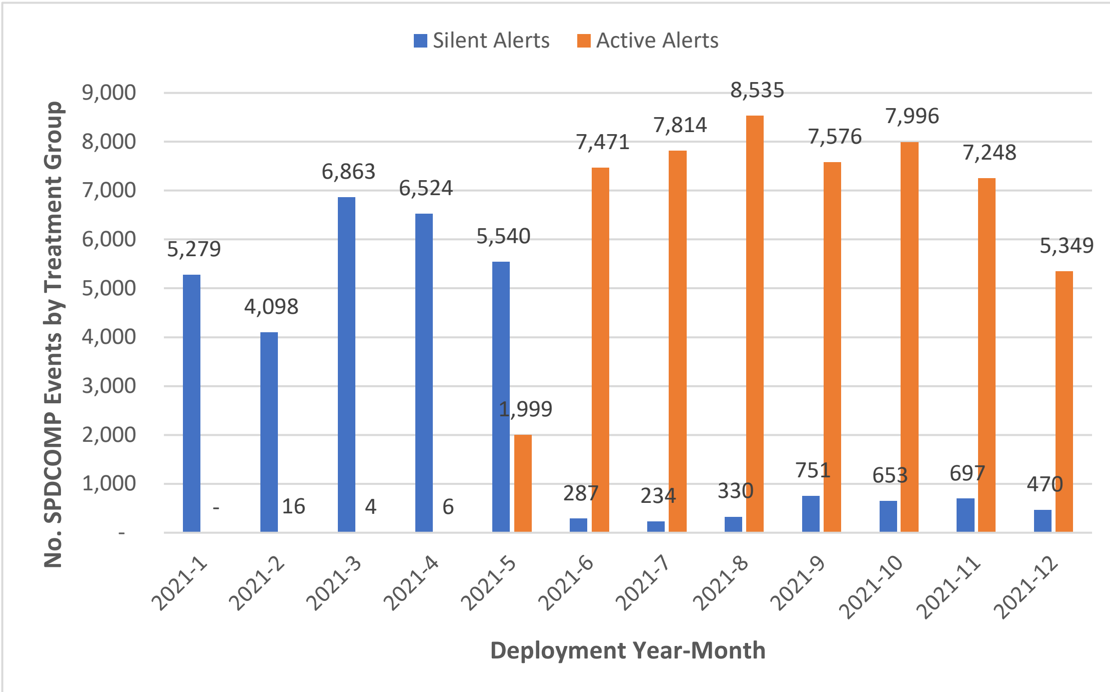


Source: U.S DOT Volpe Center

Figure 22. Distribution of All SPDCOMP Events by Alert Status and Deployment Year and Month

4.1.1.1 SPDCOMP Events Observed by Treatment Group

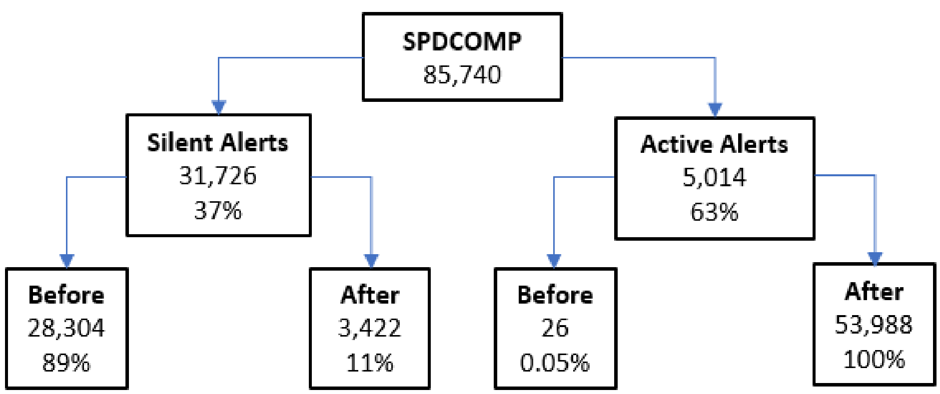
The treatment group received 85,740 SPDCOMP events (94% of all SPDCOMP events). There were 31,726 silent and 54,014 active SPDCOMP events (37% and 63%, respectively, of treatment group SPDCOMP events). Figure 23 illustrates the breakdown of silent and active SPDCOMP events for the treatment group by month during the yearlong deployment.



Source: U.S DOT Volpe Center

Figure 23. Distribution of Treatment Group SPDCOMP Events by Alert Status and Deployment Year and Month

The before period contained 28,330 treatment group SPDCOMP events (33%). The after period contained 57,410 treatment group SPDCOMP events (67%). Figure 24 breaks down the silent and active alerts by the before and after periods.



Source: U.S DOT Volpe Center

Figure 24. Breakdown of Treatment Group SPDCOMP Events by Alert Status and Deployment Period

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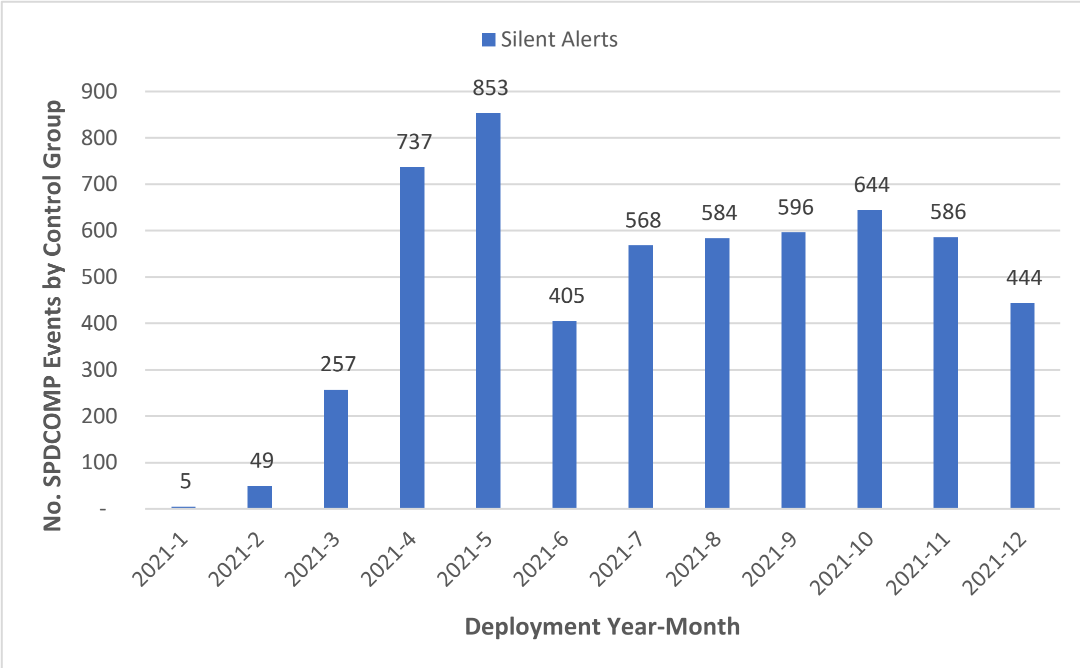
4.1.1.2 SPDCOMP Events Observed by Control Group

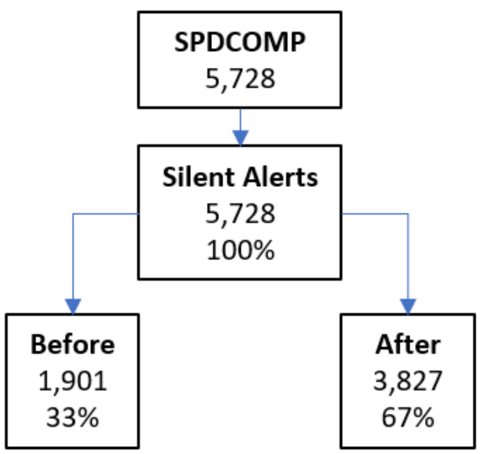
The control group experienced 5,728 SPDCOMP events (6% of all SPDCOMP events). These events comprised 5,728 silent SPDCOMP events (100%) and no active SPDCOMP events. Figure 25 breaks down the silent and active alerts by the before and after periods.



Source: U.S DOT Volpe Center

Figure 25. Distribution of Control Group SPDCOMP Events by Alert Status and Deployment Year and Month

The before period contained 1,901 control group SPDCOMP events (33%). The after period contained 3,827 control group SPDCOMP events (67%). Figure 26 breaks down the number of silent and active alerts by the before and after periods.



Source: U.S DOT Volpe Center

Figure 26. Breakdown of Control SPDCOMP Events by Alert Status and Deployment Period

4.1.2 Data Filtering of SPDCOMP Events

The Volpe team removed SPDCOMP events from the analysis due to data and alert validity issues.

4.1.2.1 SPDCOMP Events with Data Issues

The Volpe team removed some SPDCOMP events from the analysis due to data collection and processing issues, including:

1. The pre-warning or post-warning recording times were insufficient.
2. Alerts were triggered above the speed limit threshold (i.e., excessive Spd parameter was greater than 0).
3. The HV speed was unrealistic or erroneous (i.e., greater than 24.6 m/s or 55 mph).
4. Events contained less than three seconds of x-y data after the alert.

Table 4 indicates the number of discarded SPDCOMP events for each filtering condition listed above. Filtering was applied independently of the control and treatment groups, silent and active alerts, and before and after periods. The filtering process removed 2,907 SPDCOMP events (41%) of all SPDCOMP events. The Volpe team deemed the remaining 4,170 SPDCOMP events to be acceptable for further analysis.

Table 4. Filtering Results of SPDCOMP Events with Data Issues

Data Quality	Count	Percentage
Insufficient pre- or post-warning times	0	0.0%
Excessive Speed Flag	21,875	23.9%
Speed > 24.6 m/s (55 mph)	165	0.2%
Insufficient Data After Alert	806	0.9%
Good Data	68,622	75.0%
Total	91,468	100.0%

4.1.2.2 SPDCOMP Events with Invalid Alerts

The Volpe team removed SPDCOMP events from the analysis that were deemed to have experienced invalid alerts due to limitations in application capability, including the events with HV speed at alert onset below 11.2 m/s (25 mph).

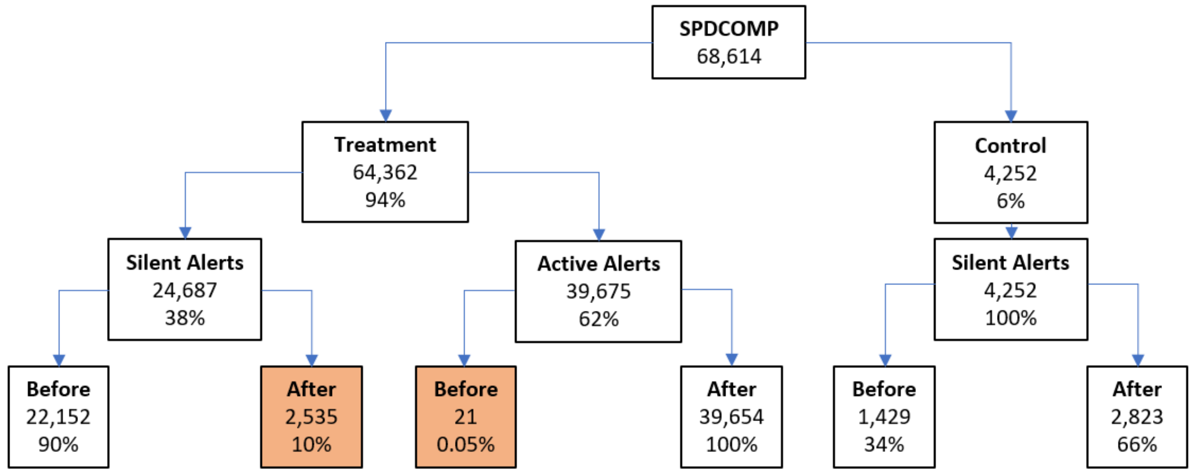
Table 5 indicates the number of discarded SPDCOMP events for the filtering condition listed above. Filtering was applied independently of the control and treatment groups, silent and active alerts, and before and after periods. The filtering process removed only eight invalid SPDCOMP events (0.01% of the acceptable SPDCOMP events). The Volpe team assessed the remaining 68,614 SPDCOMP events that were deemed to be valid for the safety impact assessment of the SPDCOMP application.

Table 5. Filtering Results of SPDCOMP Events with Invalid Alerts

Alert Validity	Count	Percentage
Speed < 11.2 m/s (25 mph)	8	0.01%
Valid	68,614	99.99%
Total	68,622	100.0%

4.1.2.3 SPDCOMP Events with Valid Alerts

The filtering of the data yielded 68,614 SPDCOMP events with valid alerts (75% of all observed SPDCOMP events). Figure 27 illustrates the breakdown of these events by treatment and control groups, silent and active alerts, and before and after periods.



Source: U.S DOT Volpe Center

Figure 27. Breakdown of Valid SPDCOMP Events by Experimental Group, Alert Status, and Deployment Period

The treatment group erroneously received 2,535 silent alerts in the after period and 21 active alerts in the before period (designated by orange cells in Figure 27). These events represent 2,556 alerts or 4% of all treatment group SPDCOMP events with valid alerts. These alerts, while valid, would generally be excluded from the safety impact analysis. The safety impact analysis normally compares the performance of the treatment group in the before period (with appropriately silent alerts) to the after period (with appropriately active alerts).

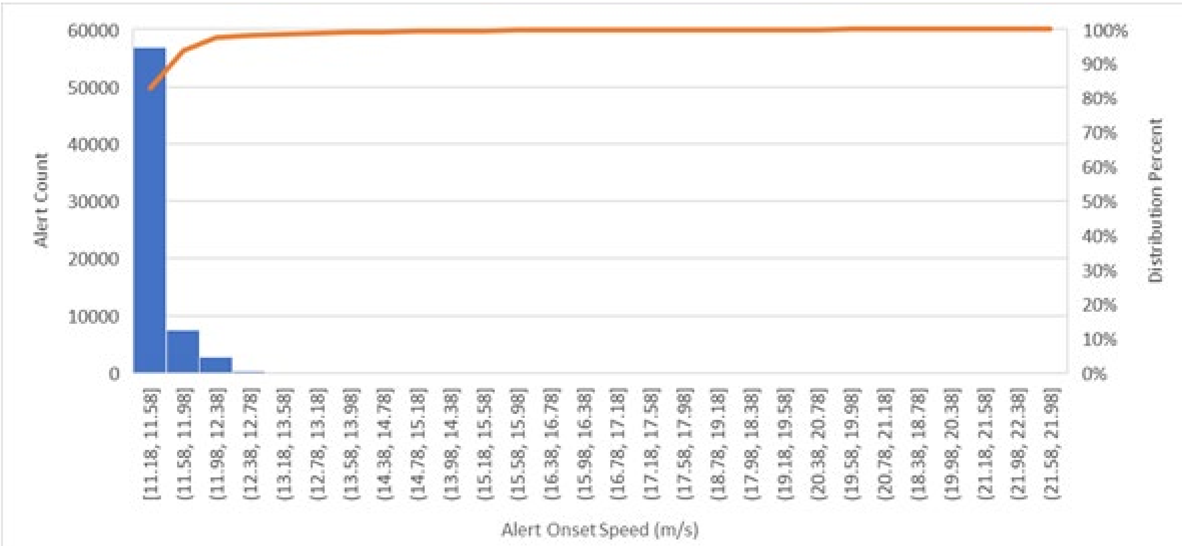
4.1.3 Analysis of Valid SPDCOMP Events

Figure 27 shows that the treatment group experienced 22,152 silent alerts in the before period and 39,654 active alerts in the after period, accounting for 36% and 64% of appropriate and valid treatment group SPDCOMP alerts, respectively. Thus, the SPDCOMP application had enough valid events with no data issues in each experimental group in the before and after periods that it was possible to perform statistical analysis using the planned experimental design. Throughout this analysis, descriptive statistics were therefore split between their respective experimental groups. For consistency with other event type analyses, these measures of performance were later performed using just the active and silent alert status for SPDCOMP events.

4.1.3.1 Initial Conditions of Valid SPDCOMP Events

The Volpe team used the HV travel speed at alert onset in meter per second (m/s), denoted $V_{HV}(0)$, as a single measure of performance to characterize initial vehicle conditions at the time of alert onset for SPDCOMP events.

As an initial step, the Volpe team examined the overall distribution of $V_{HV}(0)$ for all valid SPDCOMP events. The distribution in Figure 28 shows that over 90% of all alert events occurred between 11.18 (25.0 mph) and 11.98 m/s (26.8 mph). This is due to the design of the NYC CVP SPDCOMP application in combination with Volpe's data validity filters described previously, in which an alert was issued if the vehicle was moving above 25 mph or 11.18 m/s, the speed limit throughout NYC's local roadways. This distribution also indicates that there is no need to use multiple bins for initial conditions in the speed compliance analysis.



Source: U.S DOT Volpe Center

Figure 28. Distribution of Valid SPDCOMP Events by Travel Speed at Alert Onset

The Volpe team analyzed the parameter $V_{HV}(0)$ to determine the similarities and differences in initial HV conditions for events triggered in the different experimental groups. At SPDCOMP alert onset, treatment group vehicles in the before silent period were traveling at an average speed of 11.55 m/s (n = 22,152, variance = 0.70), while in the after active period they were traveling at an average speed of 11.34 m/s (n = 39,654, variance = 0.057). On the other hand, control group vehicles in the before period were traveling at an average speed of 11.35 m/s (n = 1,429, variance = 0.090), while in the after period they were traveling at an average speed of 11.35 m/s (n = 2,823, variance = .090). Table 6 provides additional descriptive statistics.

Table 6. Descriptive Statistics of Travel Speed (m/s) at Alert Onset for Different Experimental Groups

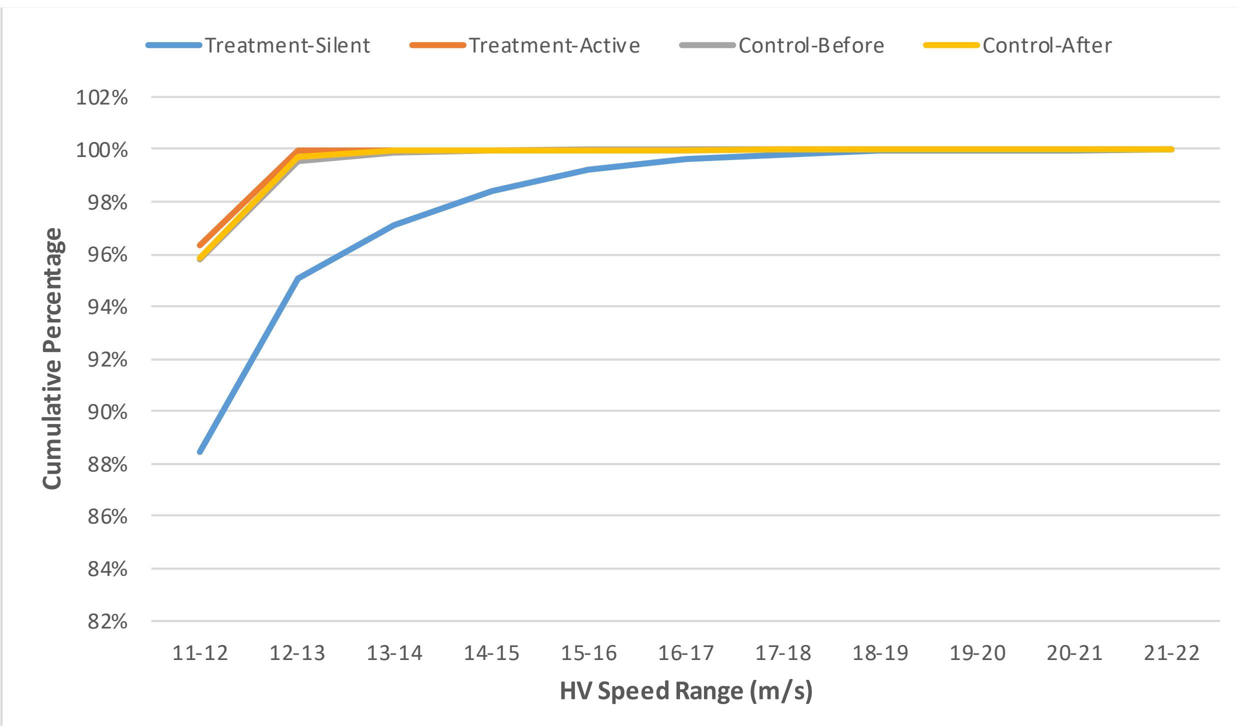
Descriptor	Treatment Before/Silent	Treatment After/Active	Control Before	Control After
Count	22,152	39,654	1,429	2,823
Mean	11.5	11.3	11.4	11.4
Standard Deviation	0.8	0.2	0.3	0.3
Minimum	11.2	11.2	11.2	11.2
Maximum	22.0	16.1	15.6	17.7

The Volpe team performed statistical comparisons between the silent and active treatment group events, the control group events in the before and after periods, and between the silent treatment group events and the control group events in the before period. Table 7 presents the results of these three comparisons.

Table 7. Statistical Comparisons of Speed at Alert Onset between Different Experimental Groups

Group 1	Group 2	T Statistic	P(T ≤ t)
Control-Before	Treatment-Before/Silent	-20.163	<<0.05
Control-Before	Control-After	-0.180	0.8573
Treatment-Before/Silent	Treatment-After/Active	35.977	<<0.05

It is desirable to observe similar distributions of alert onset speed, $V_{HV}(0)$, for the different experimental groups. However, Table 7 shows statistically-significant differences in $V_{HV}(0)$ between the treatment-before/silent and control-before groups and between the treatment-before/silent and treatment-after/active groups. Figure 29 explains these differences, with 95% of treatment-before/silent events compared to almost 100% of each of the other three experimental group events occurring below 13 m/s (29 mph).



Source: U.S DOT Volpe Center

Figure 29. Cumulative Distributions of SPDCOMP Events by HV Speed at Alert Onset for Four Experimental Groups

Even though the difference in the mean value of $V_{HV}(0)$ was statistically different between the control-before and treatment-before/silent groups (0.1 m/s or 0.2 mph) and between the treatment-before/silent and treatment-after/active groups (0.2 m/s or 0.4 mph), this difference in travel speed was practically insignificant.

4.1.3.2 Vehicle/Driver Response to Valid SPDCOMP Events

The measures of performance for vehicle/driver response after SPDCOMP alert onset included the following logical (yes or no) measures:

1. Count of events that resulted in HV speed reduction below the alert threshold – Compliance
2. Count of events that resulted in HV speed reduction greater than 2.2 m/s (5 mph) – Speed Reduced

The Volpe team also analyzed the following quantitative response measures:

1. HV minimum travel speed after alert onset (m/s) ≡ $V_{HV}(min)$
2. HV minimum speed differential after alert onset (m/s) ≡ $\Delta V_{HV}(min)$
3. Brake reaction time (s) ≡ BRT
4. HV average deceleration (m/s^2) ≡ A_{HV}

4.1.3.2.1 Analysis of Speed Limit Compliance

This logical analysis examined the rates of events that showed minimum driving speeds less than or equal to 11.18 m/s (25 mph) after the alert was issued to the driver. Table 8 shows the counts and percentages of SPDCOMP events that resulted in speed compliance and non-compliance for the treatment and control groups in the before and after periods.

Table 8. Analysis Results of SPDCOMP Alert Compliance

Experimental Group-Deployment Period	**Counts**			**Percent of Group Total**	
	Did not Comply	**Complied**	**Total**	**Did not Comply**	**Complied**
Treatment-Before	6,479	15,673	22,152	29%	71%
Treatment-After	9,174	30,480	39,654	23%	77%
Control-Before	397	1,032	1,429	28%	72%
Control-After	778	2,045	2,823	28%	72%
Total	16,828	49,230	66,058	25%	75%

Table 9 shows the results of the statistical comparisons among the different experimental groups, using the odds ratio test to compare the likelihood of drivers reducing their speed to compliance levels. As shown, the treatment-after group with active alerts was 1.37 times as likely as the treatment-before group with silent alerts to reduce their speed to 11.18 m/s or below. Results from the other comparisons did not show any statistically-significant difference in speed compliance. To account for similar initial conditions between the treatment-before/silent and treatment-after/active events ($V_{HV}(0)$ < 13 m/s), the Volpe team re-performed the odds ratio test between these two groups. The statistically-significant ($P \ll 0.05$) result showed that the treatment-after/active group was 1.27 times as likely as the treatment-before/silent group to reduce their speed to 11.18 m/s or below.

Table 9. Statistical Comparisons of Speed Limit Compliance between Different Experimental Groups

Group 1	Group 2	Odds Ratio	95% Confidence Interval	P(T ≤ t)
Control-Before	Treatment-Before/Silent	1.07	0.95 to 1.21	0.88
Control-Before	Control-After	1.01	0.87 to 1.17	0.24
Treatment-Before/Silent	Treatment-After/Active	1.37	1.32 to 1.42	<< 0.05

4.1.3.2.2 Analysis of Speed Reduction Greater than 5 MPH

This analysis examined the rate of events where drivers reduced their speed at alert onset by more than 2.24 m/s (5 mph) during the specified time interval after the alert, without increasing their speed above their speed at alert onset. In other words, the Volpe team would only mark the events as having a speed reduction if the minimum speed after the alert were more than 5 mph less than the speed at alert onset, and the maximum speed after the alert were not greater than the speed at alert onset.

Table 10 shows the counts and percentages of SPDCOMP events that resulted in speed reduction and non-reduction by greater than or equal to 2.24 m/s with brake application for the treatment and control groups in the before and after periods. Note that for the treatment-after group, the reduced-speed share of events was actually lower than the treatment-before group.

Table 10. Analysis Results of Speed Reduction in Response to SPDCOMP Alerts

Experimental Group-Deployment Period	Counts			Percents of Group Total	
	No Speed Reduction	Speed Reduction	Total	No Speed Reduction	Speed Reduction
Treatment-Before	19,437	2,715	22,152	88%	12%
Treatment-After	35,007	4,647	39,654	88%	12%
Control-Before	1,270	159	1,429	89%	11%
Control-After	2,535	288	2,823	90%	10%
Total	60,143	5,915	66,058	91%	9%

Table 11 shows the results of statistical comparisons using odds ratio tests to compare the likelihood of drivers reducing their speed by more than 2.2 m/s (5 mph) in the different experimental groups. The results show that the treatment-before group actually has a slightly higher likelihood of reducing their speed. However, having more high alert onset-speed events (i.e., greater than 13 m/s) in the treatment-before group might have affected these results. The odds ratio of 0.95 is marginally significant, with the upper-bound of the 95% confidence interval falling just below 1.00. Results from the other comparisons show no statistically-significant difference in odds for the different experimental group.

Table 11. Statistical Comparisons of Speed Reduction between Different Experimental Groups

Group 1	Group 2	Odds Ratio	95% Confidence Interval	P(T ≤ t)
Control-Before	Treatment-Before	1.12	0.94 to 1.32	0.21
Control-Before	Control-After	0.91	0.75 to 1.11	0.35
Treatment-Before	Treatment-After	0.95	0.90 to 1.00	0.048

4.1.3.2.3 Analysis of Minimum Speed after SPDCOMP Alert Onset

The Volpe team examined the HV minimum speed after alert onset, V_{HV}(min), for all valid SDPCOMP events. Table 12 presents the descriptive statistics for speed reduction levels after SPDCOMP alert onset. Table 13 shows the results of the statistical comparisons of V_{HV}(min) between the different experimenta groups, based on two-sample student's t-Test on data sets with unequal variances. The difference in HV minimum speed after SPDCOMP alert onset was only statistically-significant between the treatment-before/silent and treatment-after/active groups. In this case, there was a difference of 0.1 m/s (0.2 mph) in the average minimum speed between the treatment-before/silent and treatment-after/active groups. Practically, this difference of 0.1 m/s is physically insignificant.

Table 12. Descriptive Statistics of Minimum Speed (m/s) after SPDCOMP Alert Onset for Different Experimental Groups

Descriptor	Treatment Before/Silent	Treatment After/Active	Control Before	Control After
Count	22,152	39,654	1,429	2,823
Mean	9.3	9.2	9.2	9.3
Standard Deviation	2.97	2.78	2.92	2.81
Minimum	0	0	0	0
Median	10.48	10.28	10.46	10.5
Maximum	21.82	13.16	13.78	16.4

Table 13. Statistical Comparisons of Minimum Speed between Different Experimental Groups

Group 1	Group 2	P(T ≤ t)
Control-Before	Treatment-Before/Silent	0.093
Control-Before	Control-After	0.31
Treatment-Before/Silent	Treatment-After/Active	<< 0.05

4.1.3.2.4 Analysis of Speed Differential after SPDCOMP Alert Onset

The Volpe team studied speed differential after SPDCOMP alert onset, $\Delta V_{HV}(min)$, for all valid events that showed a reduction in speed greater than 2.24 m/s (5 mph) but not a maximum speed greater than the alert onset speed. Table 14 presents the descriptive statistics for $\Delta V_{HV}(min)$ after SPDCOMP alert onset. Table 15 shows the results of the statistical comparisons of $\Delta V_{HV}(min)$ between the different experimenta groups, based on two-sample student's t-Test on data sets with unequal variances. There was a statistically-significant difference of 0.3 m/s (0.7 mph) in the average speed reduction between treatment-before/silent and treatment-after/active vehicles. The treatment-before/silent vehicles had an overall greater average driving speed at SPDCOMP alert onset than the treatment-after/active vehicles, which allows for generally greater speed reductions after SPDCOMP alert onset.

Table 14. Descriptive Statistics of Speed Differential (m/s) after SPDCOMP Alert Onset for Different Experimental Groups

Descriptor	Treatment Before/Silent	Treatment After/Active	Control Before	Control After
Count	2,715	4,647	159	288
Mean	6.4	6.1	6.4	6.0
Standard Deviation	3.05	2.91	2.95	2.83
Minimum	2.26	2.26	2.26	2.32
Median	5.88	5.5	6.16	5.29
Maximum	17.2	12.16	12.06	11.96

Table 15. Statistical Comparisons of Speed Differential between Different Experimental Groups

Group 1	Group 2	$P(T \leq t)$
Control-Before	Treatment-Before/Silent	0.90
Control-Before	Control-After	0.15
Treatment-Before/Silent	Treatment-After/Active	<< 0.05

4.1.3.2.5 Analysis of Brake Reaction Time after SPDCOMP Alert Onset

The Volpe team examined the brake reaction time, BRT, in response to SPDCOMP alerts only for events where the brake was applied after the SPDCOMP alert was issued. Table 16 presents the descriptive statistics for BRT after SPDCOMP alert onset. Table 17 shows the results of the statistical comparisons of BRT between the different experimental groups, based on two-sample student's t-Test on data sets with unequal variances. There was a slight reduction in BRT of 0.1 s between the treatment-after/active and the treatment-before/silent groups, which was not statistically significant.

Table 16. Descriptive Statistics of Brake Reaction Time (s) after SPDCOMP Alert Onset for Different Experimental Groups

Descriptor	Treatment Before/Silent	Treatment After/Active	Control Before	Control After
Count	2,225	3,320	131	239
Mean	5.5	5.4	5.9	5.7
Standard Deviation	2.44	2.47	2.35	2.42
Minimum	0	0	1	1
Median	6	5.1	6.1	6
Maximum	9.8	9.4	9.2	9.5

Table 17. Statistical Comparisons of Brake Reaction Time between Different Experimental Groups

Group 1	Group 2	$P(T \leq t)$
Control-Before	Treatment-Before/Silent	0.05
Control-Before	Control-After	0.32
Treatment-Before/Silent	Treatment-After/Active	0.10

4.1.3.2.6 Analysis of Average Deceleration Level after SPDCOMP Alert Onset

The Volpe team analyzed the HV average deceleration level, A_{HV}, that was calculated between alert onset time and the time when the minimum speed was reached after the alert was triggered. Table 18 presents the descriptive statistics for A_{HV} after SPDCOMP alert onset.

Table 18. Descriptive Statistics of Average Deceleration Level (m/s^2) after SPDCOMP Alert Onset for Different Experimental Groups

Descriptor	Treatment Before/Silent	Treatment After/Active	Control Before	Control After
Count	15,848	25,948	853	1,691
Mean	-0.395	-0.326	-0.340	-0.332
Standard Deviation	0.37	0.31	0.32	0.32
Minimum	-5.7	-2.795	-1.8	-1.88
Median	-0.270	-0.223	-0.243	-0.227
Maximum	-0.002	-0.002	-0.002	-0.002

Table 19 shows the results of the statistical comparisons of A_{HV} between the different experimental groups, based on two-sample student's t-Test on data sets with unequal variances. There was a statistically-significant difference in the deceleration level between the treatment-before/silent and treatment-after/active groups, where the treatment-after/active group exhibited a lower deceleration level than the treatment-before/silent group.

Table 19. Statistical Comparisons of Deceleration Level between Different Experimental Groups

Group 1	**Group 2**	**P(T ≤ t)**
Control-Before	Treatment-Before/Silent	<< 0.05
Control-Before	Control-After	0.54
Treatment-Before/Silent	Treatment-After/Active	<< 0.05

4.1.4 SPDCOMP Safety Effectiveness

The SPDCOMP application was effective in reducing the following measures of performance for vehicle/driver response at the statistical confidence level over 95%:

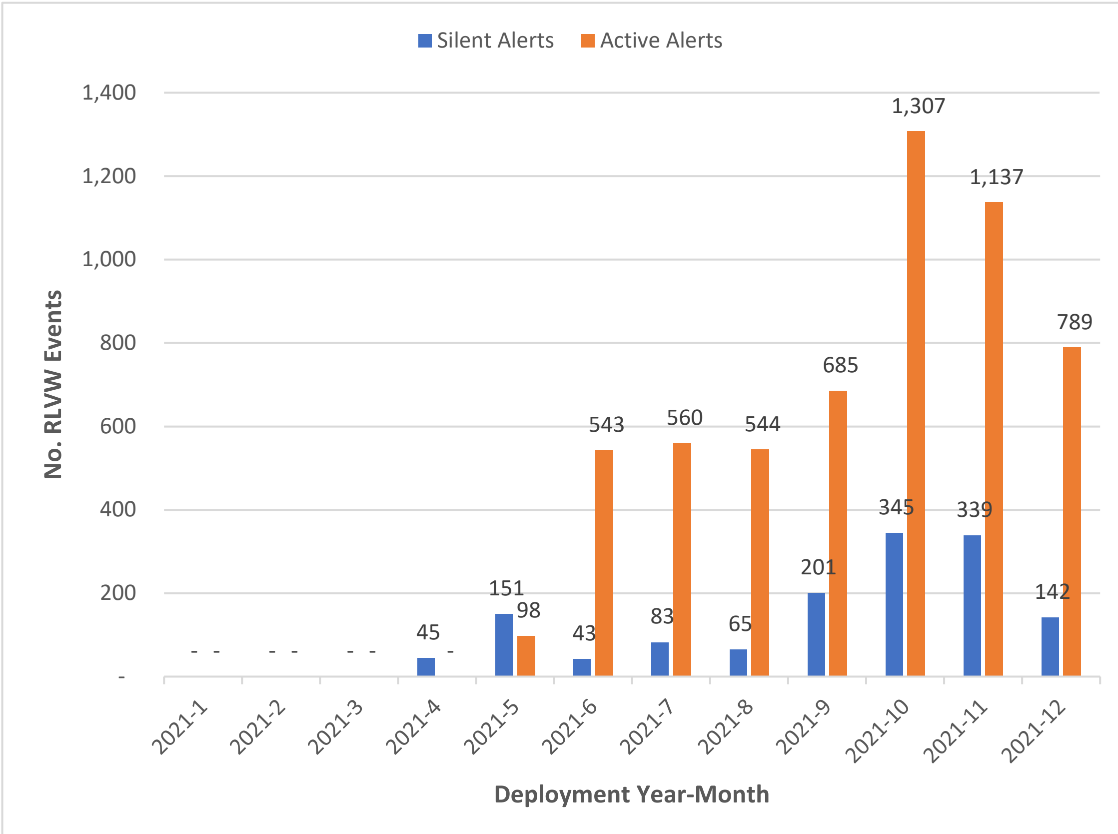
- Non-speed compliance rate from 29.2% in the treatment-before/silent alert events down to 23.1% in the treatment-after/active alert events for all initial speed conditions, with effectiveness of 21%. By accounting for similar initial speed conditions under 13 m/s, the effectiveness was 16% from 27.6% in the treatment-before/silent alert events to 23.1% in the treatment-after/active alert events.
- HV average deceleration from 0.40 m/s^2 (0.04 g) in the treatment-before/silent alert events to 0.33 m/s^2 (0.03 g) in the treatment-after/active alert events for all initial speed conditions, with effectiveness of 17%. However, this difference in average deceleration was not practically significant since the deceleration level in both event groups was very small.

The SPDCOMP application was only 2% effective in reducing the brake reaction time at 90% confidence level, from 5.5 s in the treatment-before/silent alert events to 5.4 s in the treatment-after/active alert events.

4.2 Red Light Violation Warning

4.2.1 Observed RLVW Events

The SDC contained 7,077 RLVW events from the NYC CVP deployment. These events comprised 1,414 silent RLVW events (20%) and 5,663 active RLVW events (80%). Figure 30 illustrates the breakdown of silent and active RLVW events by month during the yearlong deployment. In the before period, there were 196 RLVW events (2.8%). In the after period, there were 6,881 RLVW events (97.2%).

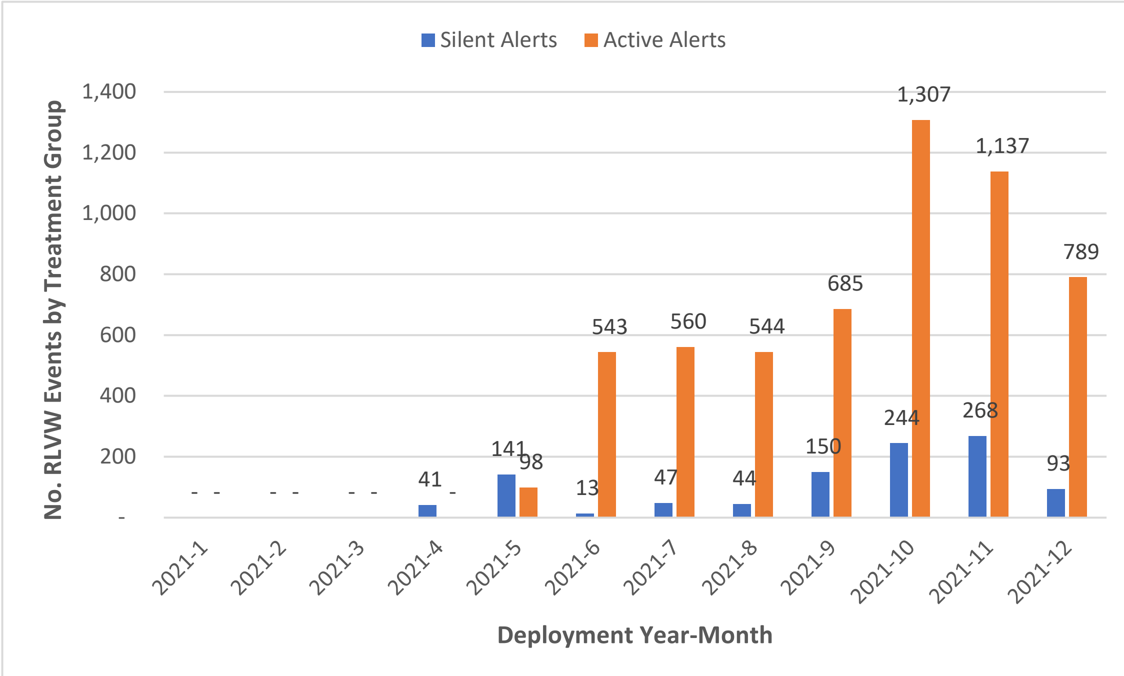


Source: U.S DOT Volpe Center

Figure 30. Distribution of All RLVW Events by Alert Status and Deployment Year and Month

4.2.1.1 RLVW Events Observed by Treatment Group

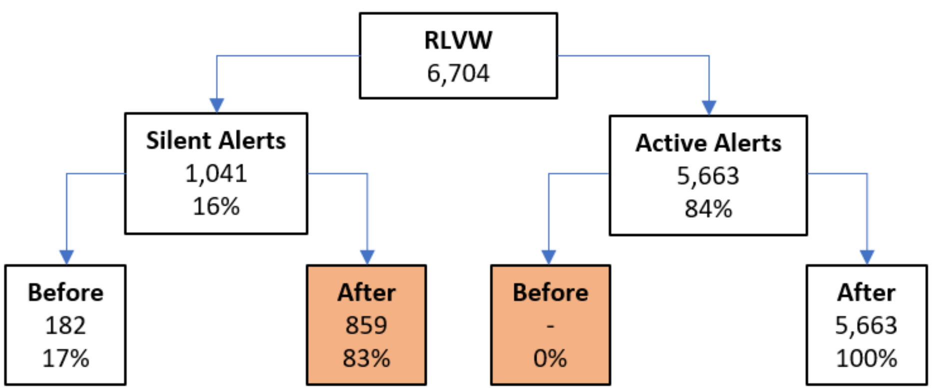
The treatment group received 6,704 RLVW events (95% of all RLVW events). There were 1,041 silent and 5,663 active RLVW events (16% and 84%, respectively, of treatment group RLVW events). Figure 31 illustrates the breakdown of silent and active RLVW events for the treatment group by month during the yearlong deployment.



Source: U.S DOT Volpe Center

Figure 31. Distribution of Treatment Group RLVW Events by Alert Status and Deployment Year and Month

The before period contained 182 treatment group RLVW events (3%). The after period contained 6,522 treatment group RLVW events (97%). Figure 32 breaks down the silent and active alerts by the before and after periods.

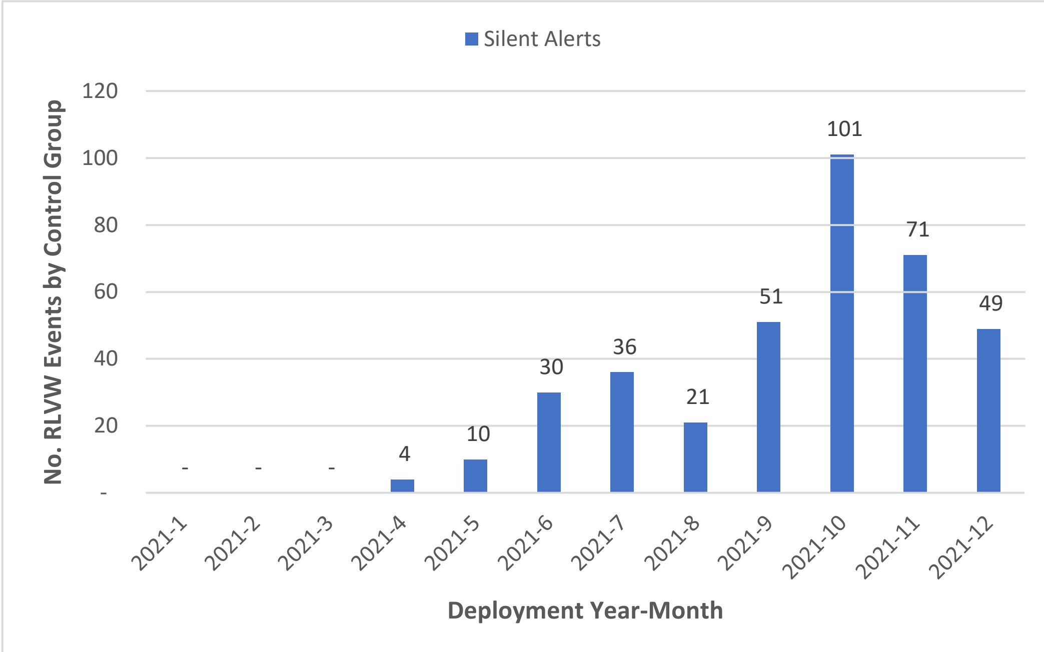


Source: U.S DOT Volpe Center

Figure 32. Breakdown of Treatment Group RLVW Events by Alert Status and Deployment Period

4.2.1.2 RLVW Events Observed by Control Group

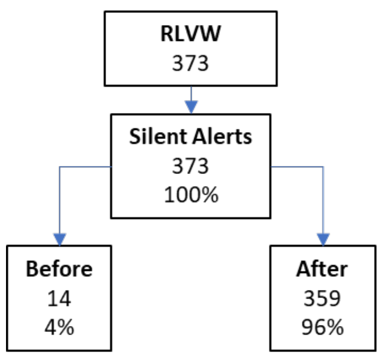
The control group experienced 373 RLVW events (5% of all RLVW events). These events comprised 373 silent RLVW events (100%) and no active RLVW events. Figure 33 illustrates the breakdown of silent and active RLVW events for the control group by month during the yearlong deployment period.



Source: U.S DOT Volpe Center

Figure 33. Distribution of Control Group RLVW Events by Alert Status and Deployment Year and Month

The before period contained 14 control group RLVW events (4%). The after period contained 359 control group RLVW events (96%). Figure 34 breaks down the number of silent and active alerts by the before and after periods.



Source: U.S DOT Volpe Center

Figure 34. Breakdown of Control RLVW Events by Alert Status and Deployment Period

4.2.2 Data Filtering of RLVW Events

The Volpe team removed RLVW events from the analysis due to data and alert validity issues. Appendix B explains the processing of MAP and SPaT data for the analysis of RLVW events.

4.2.2.1 RLVW Events with Data Issues

The Volpe team removed some RLVW events from the analysis due to data collection and processing issues, including:

1. The pre-warning or post-warning recording times were insufficient.
2. The HV did not have range or relative position data (i.e., the obfuscated GPS data was missing).
3. The HV speed was unrealistic or erroneous (i.e., greater than 24.6 m/s or 55 mph).
4. The HV x-y coordinates indicated it was stationary while the HV speed was non-zero.
5. The range from the HV to the intersection stop line increased after alert onset (i.e., the HV seemed to be moving backwards).

Table 20 indicates the number of discarded RLVW events for each filtering condition listed above. Filtering was applied independently of the control and treatment groups, silent and active alerts, and before and after periods. The filtering process removed 2,907 RLVW events (41%) of all RLVW events. The Volpe team deemed the remaining 4,170 RLVW events to be acceptable for further analysis.

Table 20. Filtering Results of RLVW Events with Data Issues

Data Quality	Count	Percentage
Insufficient pre- or post-warning times	707	10.0%
Unavailable range data	1,097	15.5%
Speed > 24.6 m/s (55 mph)	832	11.8%
Incorrect X-Y Conversion	185	2.6%
Range to intersection increased after alert	86	1.2%
Good Data	4,170	58.9%
Total	7,077	100.0%

4.2.2.2 RLVW Events with Invalid Alerts

The Volpe team removed RLVW events from the analysis that were deemed to have experienced invalid alerts due to limitations in application capability, including:

1. The HV had already entered the intersection at alert onset.
2. The range from the HV to the intersection stop line was greater than 160 m at alert onset.
3. The HV speed at alert onset was below 1.1 m/s.

Table 21 indicates the number of discarded RLVW events for each filtering condition listed above. Filtering was applied independently of the control and treatment groups, silent and active alerts, and before and after periods. The filtering process removed only 12 invalid RLVW events (0.3% of the acceptable RLVW events). The Volpe team assessed the remaining 4,158 RLVW events that were deemed to be valid for the safety impact assessment of the RLVW application.

Table 21. Filtering Results of RLVW Events with Invalid Alerts

Alert Validity	Count	Percentage
In Intersection at alert	11	0.3%
Range to Intersection Stop Line > 160 m	1	0.0%
Valid	4,158	99.7%
Total	4,170	100.0%

4.2.2.3 *RLVW Events with Valid Alerts*

The filtering of the data yielded 4,158 RLVW events with valid alerts (59% of all observed RLVW events) Figure 35 illustrates the breakdown of these events by treatment and control groups, silent and active alerts, and before and after periods.

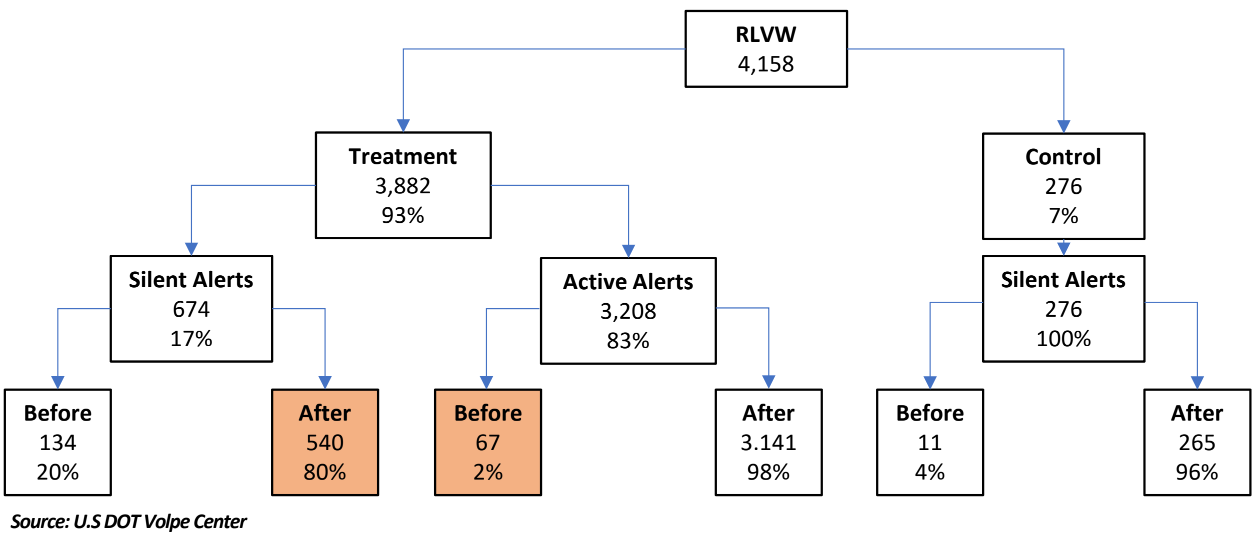


Figure 35. Breakdown of Valid RLVW Events by Experimental Group, Alert Status, and Deployment Period

The treatment group erroneously received 540 silent alerts in the after period and 67 active alerts in the before period (designated by orange cells in Figure 35). These events represent 607 alerts or 16% of all treatment group RLVW events with valid alerts. These alerts, while valid, would generally be excluded from the safety impact analysis. The safety impact analysis normally compares the performance of the treatment group in the before period (with appropriately silent alerts) to the after period (with appropriately active alerts).

Figure 35 shows that the treatment group experienced 134 silent alerts in the before period and 3,141 active alerts in the after period, accounting for 4% and 96% of appropriate and valid treatment group RLVW alerts, respectively. Thus, the number of appropriately timed silent alerts is so much smaller than the number of appropriately timed active alerts that it inhibits the ability to perform a meaningful statistical comparison of the treatment group performance between the before and after periods.

Consequently, the Volpe team decided to assess the safety impact of RLVW by comparing the response between all valid silent alerts and all valid active alerts, regardless of period (before or after) or vehicle group (treatment or control).

4.2.3 Analysis of Valid RLVW Events

The data validation process yielded 4,158 RLVW events with valid alerts for further analysis. RLVW events with silent and active alerts totaled 950 (23%) and 3,208 (77%), respectively.

4.2.3.1 Breakdown of RLVW Event Scenarios

The Volpe team divided RLVW events into two scenario groups that were distinguished by whether or not the HV crossed the intersection stop line (i.e., entered the intersection) after alert onset. Table 22 shows that the HV did not enter the intersection in 59% of all valid RLVW events. The HV did enter the intersection after the alert in 34% of the cases. The Volpe team was not able to classify 7.6% of the events due to signal status not being available at the time the vehicle entered the intersection or data not being available for long enough after the alert to determine if the vehicle eventually entered the intersection. These unknown cases were excluded from the analysis. As a result, the Volpe team performed further analysis on a total of 3,843 RLVW events that comprised 855 events with silent alerts (22.2%) and 2,988 events with active alerts (77.8%).

Table 22. Breakdown of Valid RLVW Events by Scenario

Alert Status	**HV Entered Intersection**				**HV Entered Intersection, Excluding Unknown Events**		
	No	Yes	Unknown	Total	No	Yes	Total
Silent Alerts	482	373	95	950	482	373	855
Active Alerts	1,951	1,037	220	3,208	1,951	1,037	2,988
Total	2,433	1,410	315	4,158	2,433	1,410	3,843

4.2.3.2 Analysis of HV Entering Intersection in Valid RLVW Events

The HV entered the intersection in 1,410 RLVW events after alert onset. RLVW events with silent and active alerts accounted respectively for 373 (26.5%) and 1,037 (73.5%).

4.2.3.2.1 Initial Conditions of HV Entering Intersection Scenario

The Volpe team analyzed the following measures of performance for the initial conditions of this scenario:

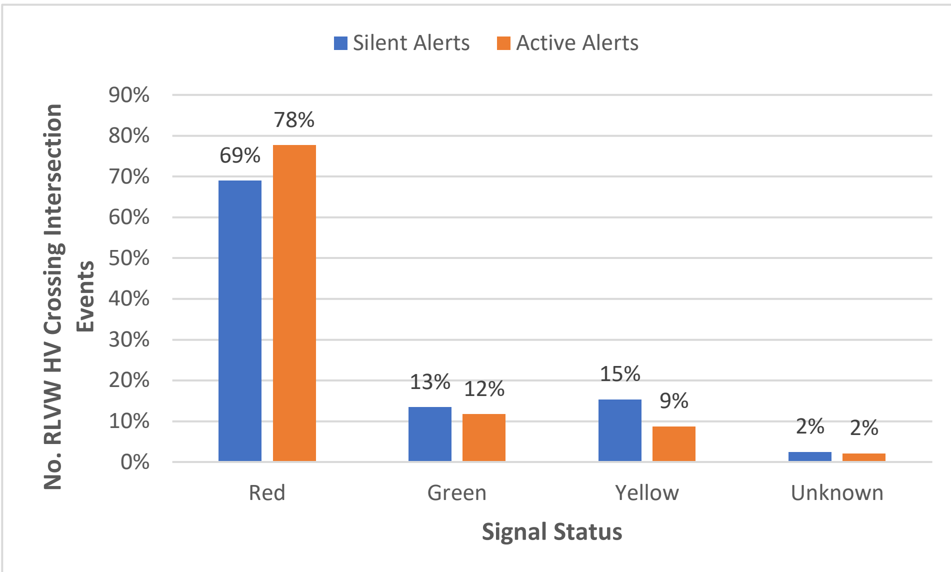
1. Status of traffic control signal at alert onset
2. $V_{HV}(0)$ (m/s)
3. HV time-to-intersection stop line at alert onset (s) ≡ $TTI_{HV}(0)$

4.2.3.2.1.1 Analysis of Signal Status at RLVW Alert Onset

Table 23 provides the breakdown of RLVW events with silent and active alerts by signal status at alert onset in the HV Entering Intersection scenario. Unknown values indicate that signal status at alert onset was not available in the data. Figure 36 illustrates the percentages of these events by alert and signal status. The majority of these events (86%) received RLVW alerts when the traffic control signal was red or yellow.

Table 23. Breakdown of RLVW HV Entering Intersection Events by Signal Status at Alert Onset

Signal Status	Silent Alerts	Active Alerts	Total
Red	257	805	1,062
Green	50	121	171
Yellow	57	90	147
Unknown	9	21	30
Total	373	1,037	1,410



Source: U.S DOT Volpe Center

Figure 36. Percentages of RLVW HV Entering Intersection Events at Alert Onset by Alert and Signal Status

For all further analyses of initial conditions in this scenario, the Volpe team excluded events with unknown signal status. Consequently, the Volpe team analyzed $V_{HV}(0)$ and $TTI_{HV}(0)$ based on 364 RLVW events with silent alert and 1,016 RLVW events with active alerts.

4.2.3.2.1.2 Analysis of HV Speed at RLVW Alert Onset

Table 24 presents the descriptive statistics of $V_{HV}(0)$ from 1,380 RLVW HV Entering Intersection events with known signal status, by signal and alert status. Table 24 also provides the results of the two-sample two-tailed student's t-Test on data sets with unequal variances between silent and active alert events.

Table 24. Descriptive Statistics of HV Speed (m/s) at Alert Onset in RLVW HV Entering Intersection Events by Signal and Alert Status

Signal Status	Alert Status	Count	Mean	StdDev	Minimum	Median	Maximum	P(T<=t)
Red	Silent	257	7.84	2.06	5.0	9.2	15.9	
	Active	805	8.13	2.34	5.0	9.1	14.6	0.06
Green	Silent	50	9.19	2.21	5.0	7.6	15.9	
	Active	121	8.86	1.99	5.0	8.0	20.7	0.37
Yellow	Silent	57	8.22	1.79	5.0	8.2	12.6	
	Active	90	8.46	2.15	5.0	8.5	15.3	0.45
All Events		1,380	8.21	2.24	5.00	8.07	20.74	0.22

The Volpe team did not observe any statistically-significant difference in $V_{HV}(0)$ between silent and active RLVW HV Entering Intersection events at over 95% confidence level.

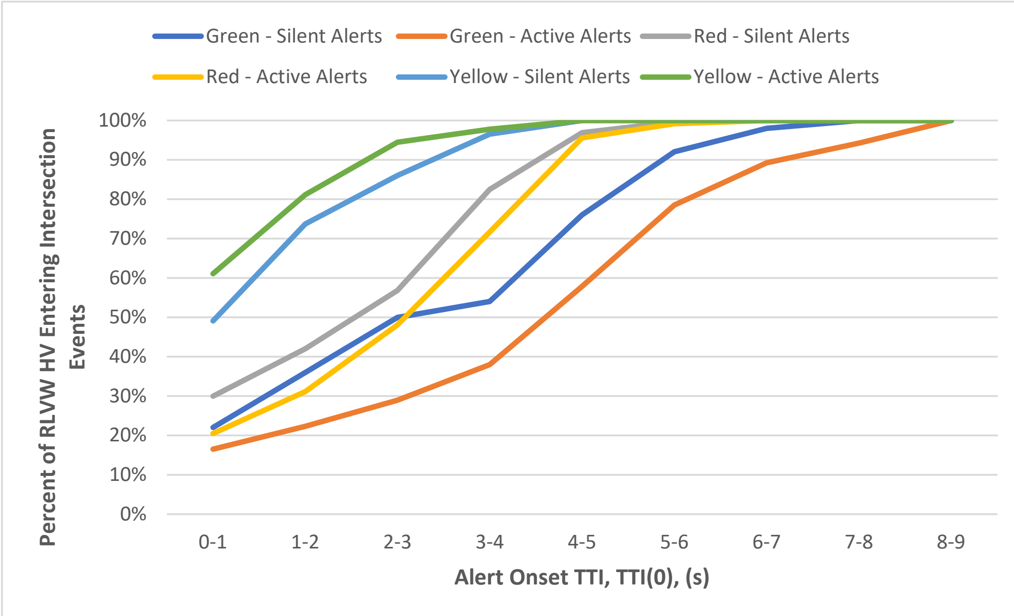
4.2.3.2.1.3 Analysis of HV Time-to-Intersection at RLVW Alert Onset

Table 25 presents the descriptive statistics of $TTI_{HV}(0)$ from 1,380 RLVW HV Entering Intersection events with known signal status, by signal and alert status. Figure 25 also provides the results of the two-sample two-tailed student's t-Test on data sets with unequal variances between silent and active alert events.

Table 25. Descriptive Statistics of $TTI_{HV}(0)$ (s) in RLVW HV Entering Intersection Events by Signal and Alert Status

Signal Status	Alert Status	Count	Mean	StdDev	Minimum	Median	Maximum	P(T<=t)
Red	Silent	257	2.35	1.62	0.1	2.6	6.1	
	Active	805	2.83	1.61	0.0	3.1	6.9	<<0.05
Green	Silent	50	3.16	2.11	0.0	3.0	7.2	
	Active	121	4.24	2.37	0.0	4.7	9.0	<< 0.05
Yellow	Silent	57	1.29	1.12	0.0	1.0	4.1	
	Active	90	1.13	0.97	0.0	0.8	4.7	0.38
All Events		1380	2.70	1.80	0.01	2.88	8.98	<< 0.05

The Volpe team observed statistically-significant differences in $TTI_{HV}(0)$ between silent and active alerts in RLVW HV Entering Intersection events under red and green signal colors ($P << 0.05$). This may call into question any statistically-significant results for vehicle/driver response in this scenario due to differences in this initial condition. Figure 37 shows the cumulative distributions of these events as a function of TTI(0) by signal and alert status.



Source: U.S DOT Volpe Center

Figure 37. Cumulative Distributions of RLVW HV Entering Intersection Events in TTI(0) Bins by Signal and Alert Status

4.2.3.2.2 Vehicle/Driver Response to RLVW HV Entering Intersection Events

The measures of performance for vehicle/driver response after RLVW alert onset in the HV Entering Intersection scenario included the following measures:

1. Red light violation count and rate
2. Time after red (s) if the HV violated the red light ≡ TaR
3. HV speed when entering the intersection ≡ $V_{HV}(EI)$

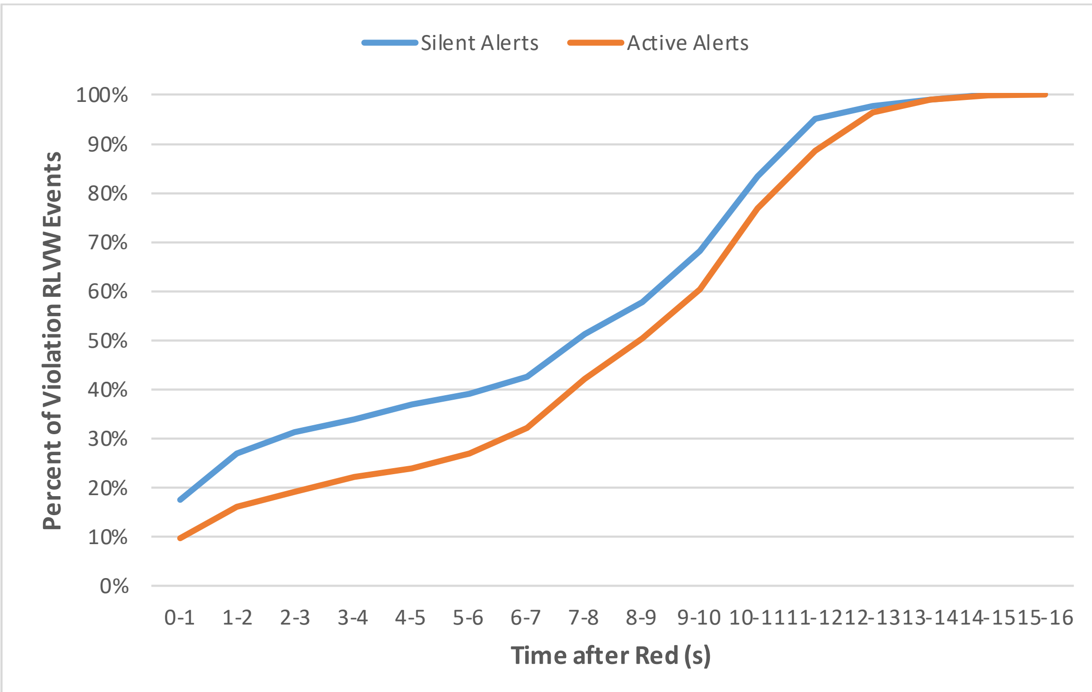
Table 26 breaks down the counts of RLVW events with silent and active alerts by violation status when the HV crossed the intersection stop line after alert onset. The Volpe Center considered an HV violation if the HV entered the intersection on red light; otherwise, there was no violation.

Table 26. Violation Results of RLVW HV Entering Intersection Events

Alert Status	Violation	Non-Violation	Total
Silent	280	93	373
Active	826	211	1,037
Total	1,106	304	1,410

In this particular scenario where the HV entered the intersection after the onset of RLVW alert, events with active alerts experienced 826 out of 1,037 (80%) red light violations. On the other hand, events with silent alerts experienced 280 out of 373 (75%) red light violations. The odds ratio test on these results showed that RLVW events with silent alerts were actually slightly less likely to experience a violation than events with active alerts in the HV Entering Intersection scenario, with marginal statistical significance (P = 0.07). It should be noted that these violation rate results don't account for RLVW events that resulted in the HV not entering the intersection after alert onset, which is discussed below.

Figure 38 shows the cumulative percentage of RLVW violation events with silent and active alerts by TaR 1-s bins. The Volpe team identified 170 events with silent alerts and 599 events with active alerts in which the HV violated the red light at greater than 6 s after the signal changed to a red light, based on the data in NYC CVP database and Volpe's SPaT and MAP processing steps. After a thorough review of the data, the Volpe team determined that these events were not trustworthy as drivers were unlikely to violate red lights that have been issued longer than 6 s prior to the driver arriving at the stop line. Therefore, the Volpe team performed further analysis of driver responses to events where the vehicle entered the intersection without including these events that had a TaR value greater than 6 s.



Source: U.S DOT Volpe Center

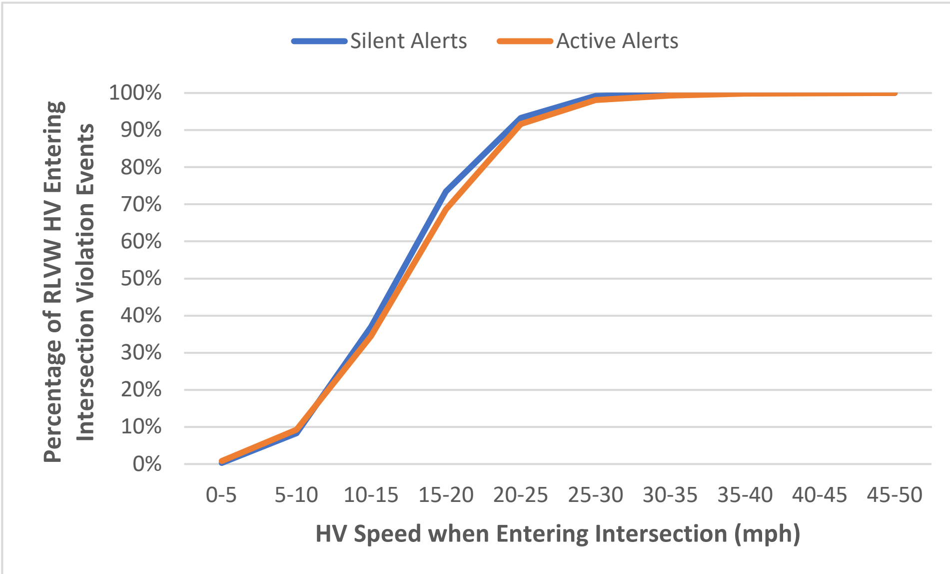
Figure 38. Cumulative Distribution of RLVW Violation Events with Silent and Active Alerts by TaR

Table 27 presents descriptive statistics of TaR for RLVW violation events in the HV Entering Intersection scenario by alert status with TaR less than or equal to 6 s. These results show that the average TaR was actually greater for events with active alerts than with silent alerts, which is statistically significant at the 95% confidence level (P = 0.02).

Table 27. Descriptive Statistics of TaR (s) for RLVW Violation Events with Silent and Active Alerts

Alert Status	Count	Mean	StdDev	Minimum	Median	Maximum
Silent	110	1.68	1.60	0	1.1	6
Active	227	2.15	1.79	0	1.5	6
Total	337	1.99	1.74	0	1.4	6

Figure 39 shows the cumulative percentage of RLVW violation events with silent and active alerts by V_{HV}(EI) 5-mph bins. In the majority of these events, the HV entered the intersection at speeds between 10 and 25 mph, with a few events having spped values of greater than 35 mph. RLVW violation events with silent and active alerts seem to have similar cumulative distributions.



Source: U.S DOT Volpe Center

Figure 39. Cumulative Distribution of RLVW Violation Events with Silent and Active Alerts by V_{HV}(EI)

Table 28 presents the descriptive statistics of V_{HV}(EI) that show no statistically-significant difference between RLVW events with silent alerts and events with active alerts at the 95% confidence level (P = 0.16).

Table 28. Descriptive Statistics of V_{HV}(EI) (mph) for RLVW Violation Events with Silent and Active Alerts

Alert Status	Count	Mean	StdDev	Minimum	Median	Maximum
Silent	280	16.2	4.8	4.57	15.7	35.2
Active	826	16.7	5.8	0.00	16.5	46.5
Total	1,106	16.6	5.5	0.00	16.3	46.5

4.2.3.2.3 Analysis of Red Light Violation Rates for All Valid RLVW Events

Table 22 in Section 4.2.3.1 provides a total count of 3,843 valid RLVW events, excluding 315 RLVW events with unknown information of signal status or HV position. A total of 855 of these events received silent alerts and 2,988 of these events received active alerts. Table 26 in Section 4.2.3.2.2 indicates that the HV violated the red light in 280 events with silent alerts (32.7% of all 855 silent alert events) and in 826 events with active alerts (27.6% of all 2,988 active alert events), including all TaR values. The odds ratio test for statistical significance shows that RLVW events with active alerts were 1.27 times more likely to avoid violating the red light than events with silent alerts. This result is statistically significant at the 95% confidence level (95% confidence interval: 1.08 to 1.50, P < .05).

By excluding red light violation events with TaR greater than 6 s from this whole analysis, 685 RLVW events with silent alerts (i.e., 855-170) experienced 110 red light violations (16.1%) and 2,389 RLVW events with active alerts (i.e., 2,988-599) experienced 227 red light violations (9.5%). The odds ratio test for statistical significance shows that RLVW events with active alerts were 1.82 times more likely to avoid violating the red light than RLVW events with silent alerts. This result is statistically significant at the 95% confidence level (95% confidence interval: 1.43 to 2.33, P << .05).

4.2.3.3 Analysis of HV Not Entering Intersection in Valid RLVW Events

The HV did not enter the intersection in 2,433 RLVW events after the alert onset. RLVW events with silent and active alerts accounted respectively for 482 (20%) and 1,951 (80%) of these events.

4.2.3.3.1 Initial Conditions of HV Not Entering Intersection Scenario

The Volpe team analyzed the following measures of performance for the initial conditions of this scenario:

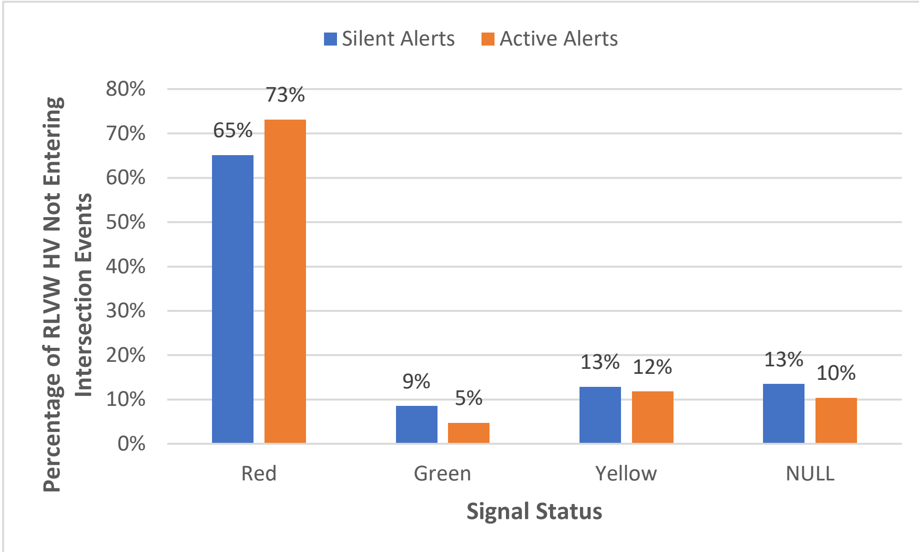
1. Status of traffic control signal at alert onset
2. $V_{HV}(0)$ (m/s)
3. $TTI_{HV}(0)$

4.2.3.3.1.1 Analysis of Signal Status at RLVW Alert Onset

Table 29 provides the breakdown of RLVW events with silent and active alerts by signal status at alert onset in the HV Not Entering Intersection scenario. Unknown values indicate that signal status at alert onset was not available in the data. Figure 46 illustrates the percentages of these events by alert and signal status. The majority of these events (84%) received RLVW alerts when the traffic control signal was red or yellow.

Table 29. Breakdown of RLVW HV Not Entering Intersection Events by Signal Status at Alert Onset

Signal Status	Silent Alerts	Active Alerts	Total
Red	314	1,426	1,740
Green	41	92	133
Yellow	62	230	292
Unknown	65	203	268
Total	482	1,951	2,433



Source: U.S DOT Volpe Center

Figure 40. Percentages of RLVW HV Not Entering Intersection Events at Alert Onset by Alert and Signal Status

For all further analyses of initial conditions in this scenario, the Volpe team excluded events with unknown signal status. Consequently, the Volpe team analyzed $V_{HV}(0)$ and $TTI_{HV}(0)$ based on 417 RLVW events with silent alerts and 1,748 RLVW events with active alerts.

4.2.3.3.1.2 Analysis of HV Speed at RLVW Alert Onset

Table 30 presents the descriptive statistics of $V_{HV}(0)$ from 2,165 RLVW HV Not Entering Intersection events with known signal status, by signal and alert status.

Two-sample two-tailed student's t-Test on data sets with unequal variances of $V_{HV}(0)$ across all signal colors between events with silent and active alerts did not show any statistically-significant differences (P = 0.14). This gives assurance that vehicle/driver responses to RLVW alerts in HV Not Entering Intersection scenario can be compared reliably later on in the analysis.

Table 30. Descriptive Statistics of HV Speed (m/s) at Alert Onset in RLVW HV Not Entering Intersection Events by Signal and Alert Status

Signal Status	Alert Status	Count	Mean	StdDev	Minimum	Median	Maximum	P (T ≤ t)
Red	Silent	314	8.13	1.84	5.0	8.1	12.8	0.83
	Active	1,426	8.10	1.71	5.0	8.0	17.6	
Green	Silent	41	8.16	1.83	5.1	8.2	12.9	0.113
	Active	92	7.62	1.72	5.0	7.5	11.3	
Yellow	Silent	62	8.48	2.11	5.1	8.1	13.9	0.017
	Active	230	7.78	1.64	5.0	7.7	12.3	

4.2.3.3.1.3 Analysis of HV Time to Intersection at RLVW Alert Onset

Table 31 presents the descriptive statistics of $TTI_{HV}(0)$ from 2,165 RLVW HV Not Entering Intersection events with known signal status, by signal and alert status.

Table 31. Descriptive Statistics of $TTI_{HV}(0)$ (s) in RLVW HV Not Entering Intersection Events by Signal and Alert Status

Signal Status	Alert Status	Count	Mean	StdDev	Minimum	Median	Maximum	P(T ≤ t)
Red	Silent	314	4.36	2.81	0.1	3.9	19.9	0.375
	Active	1,426	4.25	2.32	1.0	3.9	20.4	
Green	Silent	41	4.87	4.30	0.2	4.0	17.8	0.557
	Active	92	5.55	4.99	1.0	3.6	20.0	
Yellow	Silent	62	3.48	1.95	0.8	3.3	14.8	0.189
	Active	230	3.09	1.28	0.5	2.9	15.1	

Two-sample two-tailed student's t-Test on data sets with unequal variances of $TTI_{HV}(0)$ across all signal colors between events with silent and active alerts did not show any statistically-significant differences (P = 0.45). This gives assurance that vehicle/driver responses to RLVW alerts in HV Not Entering Intersection scenario can be compared reliably later on in the analysis.

4.2.3.3.2 Vehicle/Driver Response to RLVW HV Not Entering Intersection Events

The Volpe team analyzed the following measures of performance for vehicle/driver response to RLVW alerts in events where the HV did not enter the intersection:

1. Brake application
2. BRT (s)
3. A_{HV} (m/s^2)
4. HV peak deceleration (m/s^2) ≡ Ap_{HV}

4.2.3.3.2.1 Analysis of Brake Application After RLVW Alert Onset

The Volpe team identified 891 RLVW events where the HV applied the brakes in the HV Not Entering Intersectin scenario after alert onset, excluding 145 events with brake application at alert onset. The HV did not brake in this scenario after RLVW alert onset in 1,397 events. Table 32 presents the breakdown of RLVW HV Not Entering Intersection events by brake application and alert status. The HV braked in 39% of such events with active alerts and 38% of such events with silent alerts. The odds ratio test of these results indicated that drivers were 1.04 times more likely to apply the brakes when receiving active alerts compared to silent aerts, which is quite insignificant (P = 0.70).

Table 32. Counts of RLVW HV Not Entering Intersection Events by Brake Application and Alert Status

Alert Status	Did Not Brake	Braked	Total
Silent	279	172	451
Active	1,118	719	1,837
Total	1,397	891	2,288

Of the 891 events where the HV applied the brakes, the HV decelerated to a stop in 687 or 77% of these events. Table 33 presents the breakdown of RLVW HV Not Entering Intersection events with brake application by whether the HV came to a stop and by alert status. The HV stopped in 77.1% of such events with active alerts and 77.3% of such events with silent alerts. The odds ratio test showed no statistically-significant difference in the likelihood of the HV decelerating to a stop in response to active or silent alerts (P = 0.97).

Table 33. Counts of RLVW HV Not Entering Intersection Events with Brake Application by Stopping and Alert Status

Alert Status	Did Not Stop	Stopped	Total
Silent	39	133	172
Active	165	554	719
Total	204	687	891

4.2.3.3.2.2 Analysis of Brake Reaction Time After RLVW Alert Onset

Table 34 presents the descriptive statistics of HV brake reaction time in RLVW HV Not Entering Intersection events with brake application, as well as the results of the two-sample two-tailed student's t-Test on data sets with unequal variances between silent and active alert events. For all braking events, the HV exhibited shorter reaction time with active alerts (2.53 s) than with silent alerts (2.87 s). Similar result was observed in events where the HV decelerated to a stop. In both cases, the results were statistically significant at 95% and higher confidence levels.

Table 34. Descriptive Statistics and Statistical Test Results of Brake Reaction Time (s) in RLVW HV Not Entering Intersection Events with Brake Application by Brake Outcome and Alert Status

Brake Outcome Events	Alert Status	Count	Mean	StdDev	Minimum	Median	Maximum	P(T≤t)
Brake Response - All	Silent	172	2.87	1.59	0.10	2.70	7.50	0.01
	Active	719	2.53	1.39	0.10	2.40	7.70	
Brake Response - Decelerated to Stop	Silent	133	2.75	1.47	0.30	2.70	7.50	0.05
	Active	554	2.48	1.28	0.10	2.40	7.50	

4.2.3.3.2.3 Analysis of Deceleration Levels after RLVW Alert Onset

Table 35 and Table 36 present the descriptive statistics of HV average and peak deceleration levels in RLVW HV Not Entering Intersection events with brake application, as well as the results of the two-sample two-tailed student's t-Test on data sets with unequal variances between silent and active alert events, respectively for all and for HV stopping brake events. All results of these two measures of performance were not statistically significant.

Table 35. Descriptive Statistics and Statistical Test Results of Deceleration Levels in All RLVW HV Not

Entering Intersection Braking Events

Response Measure	Alert Status	Count	Mean	StdDev	Minimum	Median	Maximum	P(T ≤ t)
A_{HV} (m/s²)	Silent	172	-1.19	0.26	-2.01	-1.17	-0.44	0.24
	Active	719	-1.16	0.28	-2.69	-1.13	-0.55	
Ap_{HV} (m/s²)	Silent	172	-2.41	0.38	-3.77	-2.33	-2.0	0.97
	Active	719	-2.42	0.43	-5.55	-2.3	-2.0	

Table 36. Descriptive Statistics and Statistical Test Results of Deceleration Levels in Stopping RLVW HV Not Entering Intersection Braking Events

Response Measure	Alert Status	Count	Mean	StdDev	Minimum	Median	Maximum	P(T ≤ t)
A_{HV} (m/s²)	Silent	133	-1.17	0.26	-1.92	-1.15	-0.44	0.44
	Active	554	-1.15	0.28	-2.69	-1.13	-0.55	
Ap_{HV} (m/s²)	Silent	133	-2.41	0.38	-3.77	-2.31	-2	0.50
	Active	554	-2.43	0.45	-5.55	-2.3	-2	

4.2.4 RLVW Safety Effectiveness

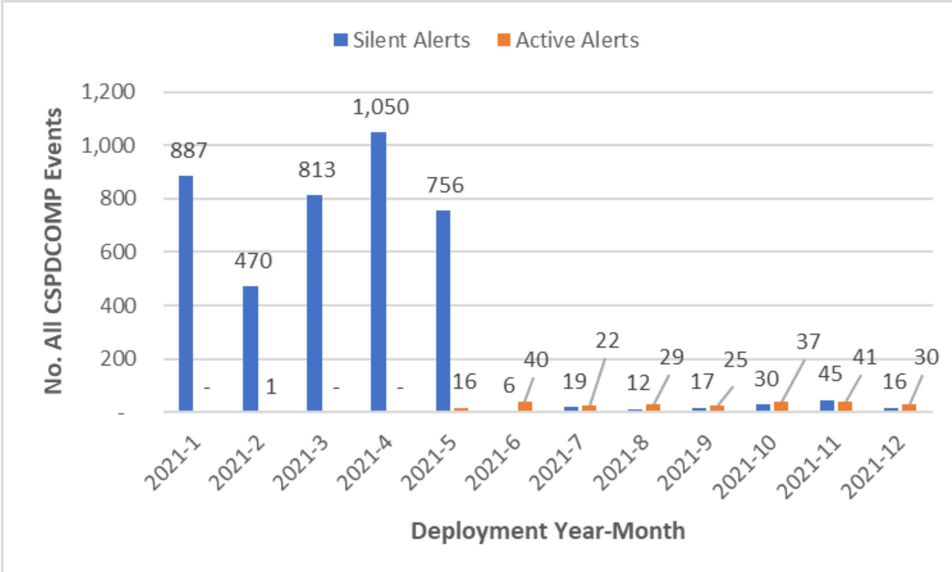
The RLVW application was effective in reducing the following measures of performance for vehicle/driver response at the statistical confidence level over 95%:

- Red light violation rate from 32.7% in RLVW events with silent alerts down to 27.6% in such events with active alerts by including all TaR values, with effectiveness of 15.6%.
- Red light violation rate from 16.1% in RLVW events with silent alerts down to 9.5% in such events with active alerts by excluding TaR values > 6 s, with effectiveness of 40.8%.

4.3 Curve Speed Compliance

4.3.1 Observed CSPDCOMP Events

The SDC contained 4,362 CSPDCOMP events from the NYC CVP deployment. These events comprised 4,121 silent SPDCOMP events (94%) and 241 active CSPDCOMP events (6%). Figure 41 illustrates the breakdown of silent and active speed compliance events by month during the yearlong deployment. In the before period, there were 3,977 CSPDCOMP events (91%). In the after period, there were 385 CSPDCOMP events (9%).

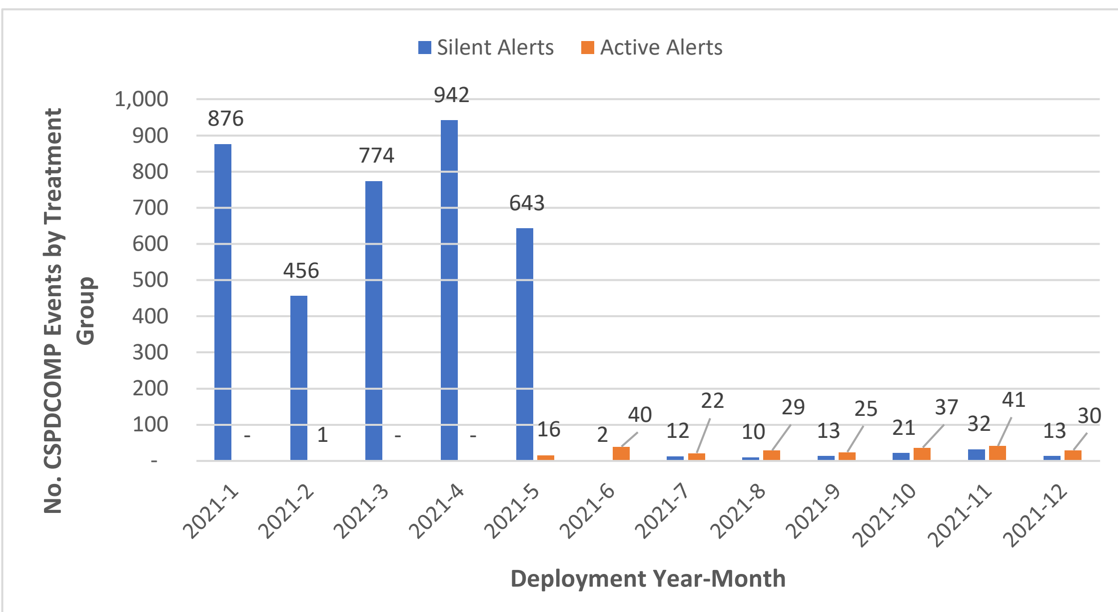


Source: U.S DOT Volpe Center

Figure 41. Distribution of All CSPDCOMP Events by Alert Status and Deployment Year and Month

4.3.1.1 Observed CSPDCOMP Events by Treatment Group

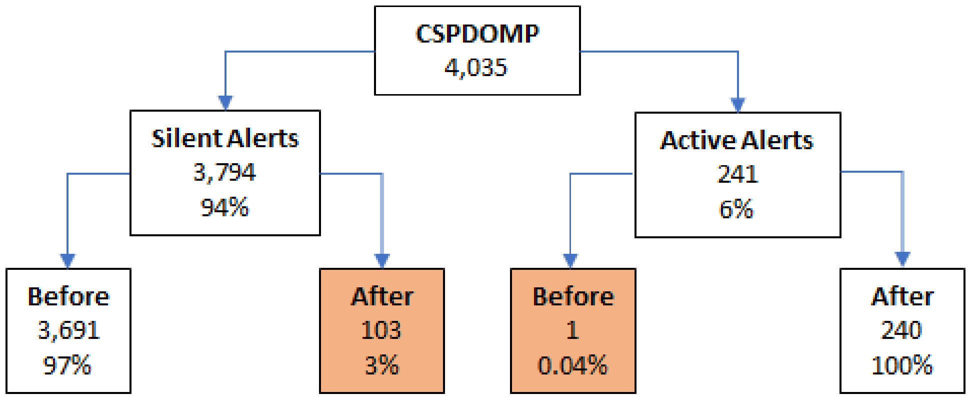
The treatment group received 4,035 CSPDCOMP events (93% of all CSPDCOMP events). There were 3,794 silent and 241 active SPDCOMP events (94% and 6%, respectively, of treatment group CSPDCOMP events). Figure 42 illustrates the breakdown of silent and active CSPDCOMP events for the treatment group by month during the yearlong deployment.



Source: U.S DOT Volpe Center

Figure 42. Distribution of Treatment Group CSPDCOMP Events by Alert Status and Deployment Year and Month

The before period contained 3,692 treatment group CSPDCOMP events (91%). The after period contained 343 treatment group CSPDCOMP events (9%). Figure 43 breaks down the silent and active alerts by the before and after periods.

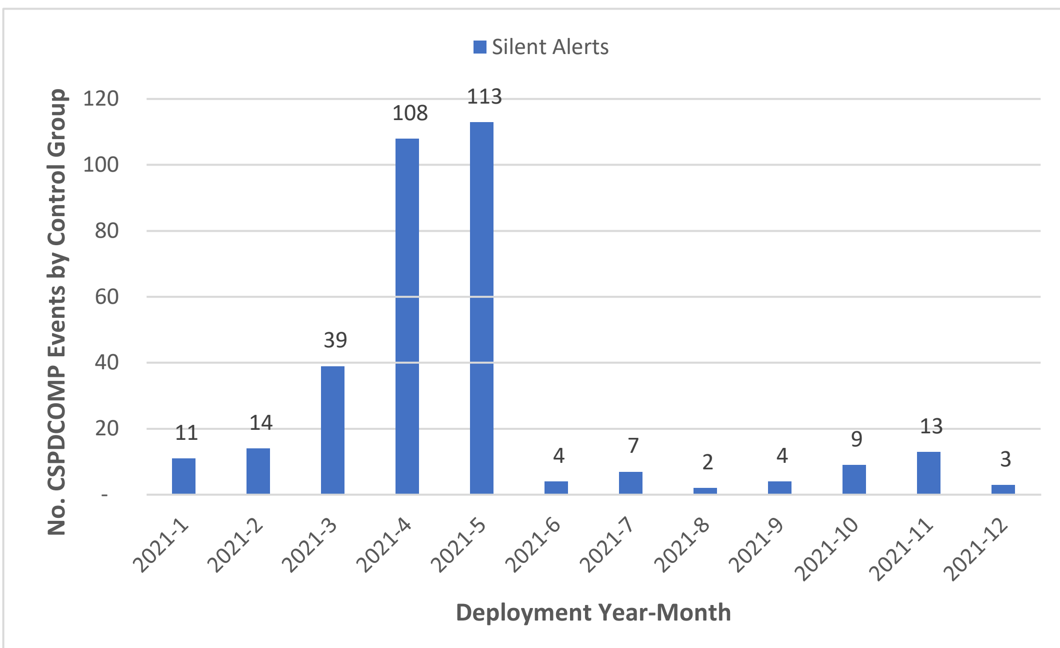


Source: U.S DOT Volpe Center

Figure 43. Breakdown of Treatment Group CSPDCOMP Events by Alert Status and Deployment Period

4.3.1.2 CSPDCOMP Events Observed by Control Group

The control group experienced 327 CSPDCOMP events (7% of all CSPDCOMP events). These events comprised 327 silent CSPDCOMP events (100%) and no active CSPDCOMP events. Figure 44 illustrates the breakdown of silent and active CSPDCOMP events for the control group by month during the yearlong deployment period.



Source: U.S DOT Volpe Center

Figure 44. Distribution of Control Group CSPDCOMP Events by Alert Status and Deployment Year and Month

The before period contained 285 control group CSPDCOMP events (87%). The after period contained 42 control group CSPDCOMP events (13%). Figure 53 breaks down the number of silent and active alerts by the before and after periods.

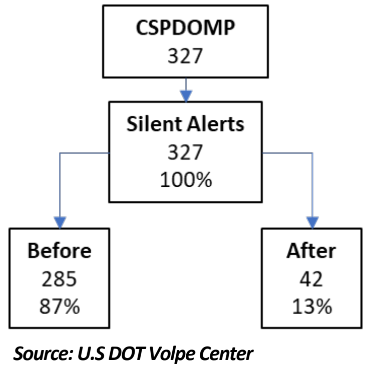


Figure 45. Breakdown of Control Group CSPDCOMP Events by Alert Status and Deployment Period

4.3.2 Data Filtering of CSPDCOMP Events

The Volpe team removed CSPDCOMP events from the analysis due to data and alert validity issues.

4.3.2.1 CSPDCOMP Events with Data Issues

The Volpe team removed some CSPDCOMP events from the analysis due to data collection and processing issues, including:

1. The pre-warning or post-warning recording times were insufficient.
2. Alerts were triggered above the speed limit threshold (i.e., excessiveCurveSpd parameter was greater than 0).
3. The HV speed was unrealistic or erroneous (i.e., greater than 24.6 m/s or 55 mph).
4. Events contained less than three seconds of x-y data after the alert.

Table 36 indicates the number of discarded CSPDCOMP events for the third and fourth filtering conditions listed above. The first two conditions did not apply to any event. Filtering was applied independently of the control and treatment groups, silent and active alerts, and before and after periods. The filtering process removed 659 CSPDCOMP events (15%) of all CSPDCOMP events. The Volpe team deemed the remaining 3,703 CSPDCOMP events to be acceptable for further analysis.

Table 37. Filtering Results of CSPDCOMP Events with Data Issues

Data Quality	Count	Percentage
Speed > 24.6 m/s (55 mph)	376	8.6%
Insufficient Data after Alert	283	6.5%
Good Data	3,703	84.9%
Total	4,362	100.0%

4.3.2.2 CSPDCOMP Events with Invalid Alerts

The Volpe team removed CSPDCOMP events from the analysis that were deemed to have experienced invalid alerts due to limitations in application capability, including:

1. Incorrect triggering locations (Path with low curvature; i.e., yaw value less than 0.22 radian.) Note: The Volpe team developed this threshold from the yaw values observed in validated CSPDCOMP events using the event visualization tool and data analysis.
2. The HV speed at alert onset was below the minimum speed threshold of 11.2 m/s (25 mph).

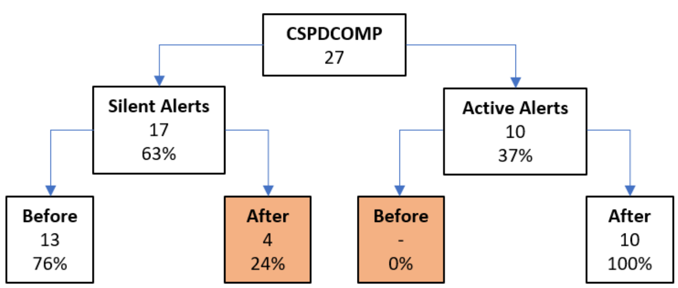
Table 38 indicates the number of discarded CSPDCOMP events for the filtering conditions listed above. Filtering was applied independently of the control and treatment groups, silent and active alerts, and before and after periods. The filtering process removed 3,674 invalid CSPDCOMP events (99% of the acceptable CSPDCOMP events), yielding only 29 valid CSPDCOMP events for further analysis.

Table 38. Filtering Results of CSPDCOMP Events with Invalid Alerts

Alert Validity	Count	Percentage
Not Approaching a Curve	3,272	88.4%
Speed < 11.2 m/s (25 mph)	402	10.9%
Valid	29	0.8%
Total	3,703	100.0%

4.3.2.3 CSPDCOMP Events with Valid Alerts

Data filtering of CSPDCOMP events resulted in a total of only 29 events (0.7% of all observed CSPDCOMP events). The treatment group experienced 27 of these events. Figure 46 illustrates the breakdown of the 27 CSPDCOMP treatment group events by silent and active alerts and by before and after periods. The treatment group erroneously received 4 silent alerts in the after period and no active alerts in the before period (red cells in Figure 46). These events represent 15% of all treatment group CSPDCOMP events with valid alerts. The control group had only 2 silent alerts, both in the before period.



Source: U.S DOT Volpe Center

Figure 46. Breakdown of Valid CSPDCOMP Events by Alert Status and Deployment Period

The Volpe team decided to assess the safety impact of CSPDCOMP by comparing the response between all 19 valid silent alerts and all 10 valid active alerts, regardless of period (before or after) or vehicle group (treatment or control).

4.3.3 Analysis of Valid CSPDCOMP Events

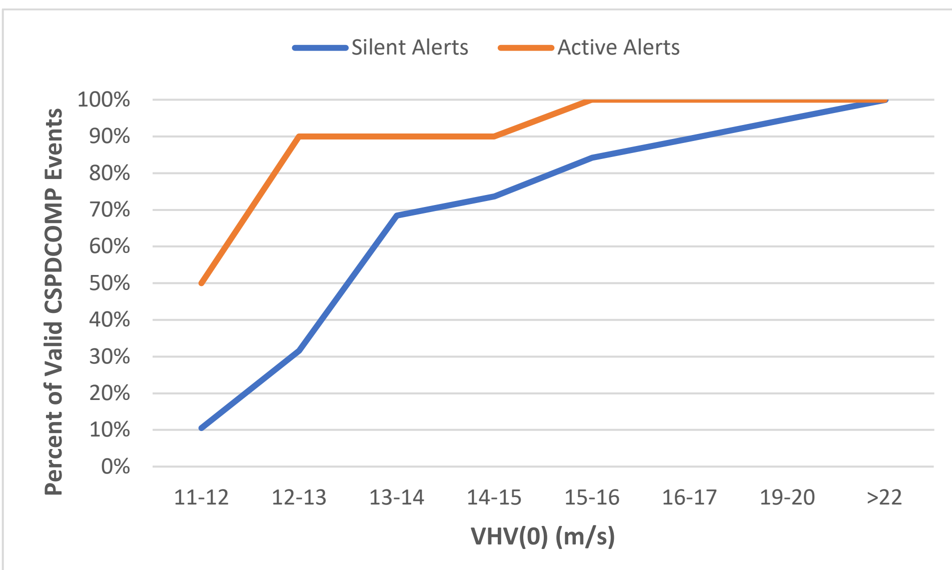
The data validation process yielded only 29 CSPDCOMP events with valid alerts for further analysis. CSPDCOMP events with silent and active alerts accounted respectively for 66% and 34% of all these events.

4.3.3.1 Initial Conditions of Valid CSPDCOMP Events

The Volpe team used the HV travel speed at alert onset as a single measure of performance to characterize initial vehicle conditions at the time of alert onset for CSPDCOMP events. Table 39 presents the descriptive statistics of HV speed at alert onset in CSPDCOMP events, and the result of the two-sample two-tailed student's t-Test on data sets with unequal variances between silent and active alert events. The HV travel speed at alert onset was higher in silent alert events (14.2 m/s) than in active alert events (12.4 m/s), which is statistically-significant at 97% confidence level. Figure 47 shows that 90% of valid CSPDCOMP events with active alerts occurred at travel speeds under 13 m/s, as opposed to only about 30% of such events with silent alerts.

Table 39. Descriptive Statistics and Statistical Test Results of HV Speed at Alert Onset (m/s) in Valid CSPDCOMP Events by Alert Status

Alert Status	Count	Mean	StdDev	Minimum	Median	Maximum	$P(T \leq t)$
Silent	19	14.2	2.92	11.34	13.3	23.1	0.03
Active	10	12.4	1.14	11.4	12.12	15.22	



Source: U.S DOT Volpe Center

Figure 47. Cumulative Distributions of Valid CSPDCOMP Events with Silent and Active Alerts by $V_{HV}(0)$

4.3.3.2 Vehicle/Driver Response to Valid CSPDCOMP Events

The Volpe team analyzed the following two measures of performance for vehicle/driver response to CSPDCOMP events:

1. $V_{HV}(min)$ m/s

2. $\Delta V_{HV}(min)$ m/s

Table 39 presents the descriptive statistics of these two measures in CSPDCOMP events, and the results of the two-sample two-tailed student's t-Test on data sets with unequal variances between silent and active alert events. Events with active alerts experienced smaller minimum travel speed after alert onset (10 m/s) than events with silent alerts (13.6 m/s). The HV minimum speed differential after alert onset was larger in events with active alerts (2.4 m/s) than in events with silent alerts (0.6 m/s). These two results are statistically significant. Since travel speed at alert onset was larger in silent alert events than in active alert events, one would expect a higher minimum speed differential after alert onset from silent alert events. Thus, this result indicates that the CSPDCOMP application was effective in reducing the travel speed.

Table 40. Descriptive Statistics and Statistical Test Results of $V_{HV}(min)$ and $\Delta V_{HV}(min)$ in Valid CSPDCOMP Events by Alert Status

Response Measure	Alert Status	Count	Mean	StdDev	Minimum	Median	Maximum	P(T≤t)
$V_{HV}(min)$ m/s	Silent	19	13.59	3.23	8.82	13.18	21.8	<< 0.05
	Active	10	10.02	1.17	7.9	10.47	11.26	
$\Delta V_{HV}(min)$ m/s	Silent	19	0.60	0.91	0	0	2.58	<< 0.05
	Active	10	2.37	1.25	0.94	2.2	4.32	

4.3.4 CSPDCOMP Safety Effectiveness

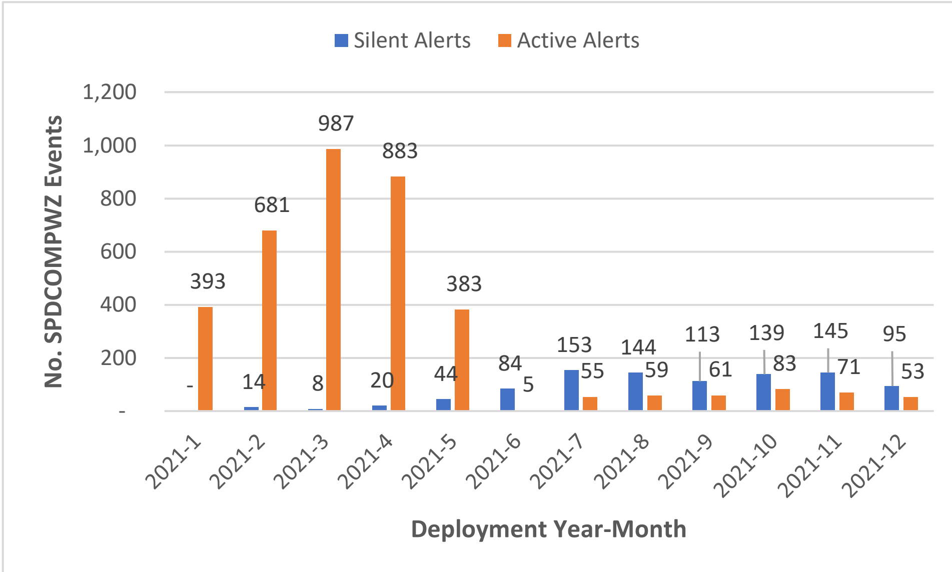
The CSPDCOMP application was effective at the statistical confidence level over 95% in:

- Reducing the minimum travel speed after alert onset from 13.6 m/s in events with silent alerts to 10.02 m/s in events with active alerts, with 26% effectiveness.
- Increasing the minimum speed differential after alert onset from 0.6 m/s in events with silent alerts to 2.37 m/s in events with active alerts, with 294% effectiveness.

4.4 Work Zone Speed Compliance

4.4.1 Observed SPDCOMPWZ Events

The SDC contained 4,673 SPDCOMPWZ events from the NYC CVP deployment. These events comprised 3,714 silent SPDCOMPWZ events (79%) and 959 active SPDCOMPWZ events (21%). Figure 48 illustrates the breakdown of silent and active speed compliance events by month during the yearlong deployment. In the before period, there were 3,369 SPDCOMPWZ events (72%). In the after period, there were 1,304 SPDCOMPWZ events (28%).

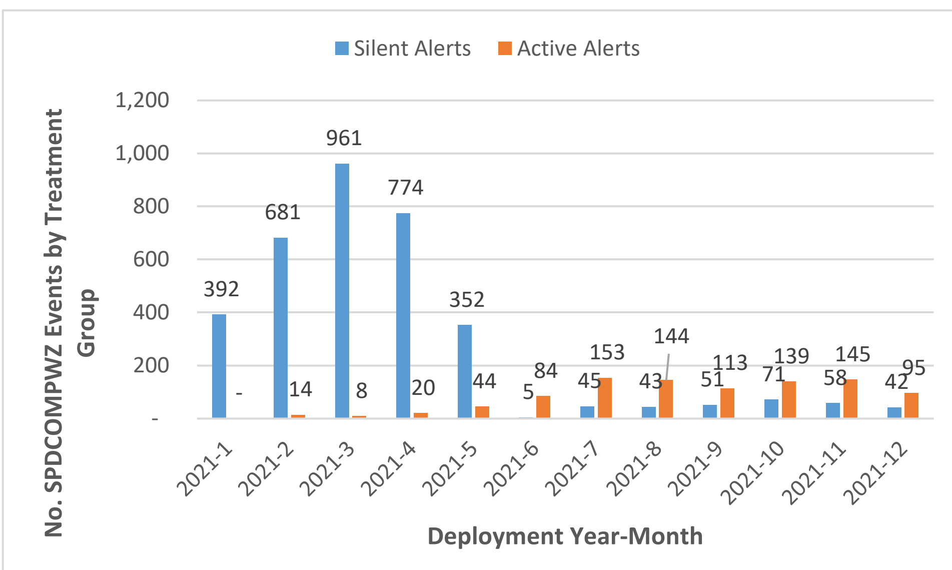


Source: U.S DOT Volpe Center

Figure 48. Distribution of All SPDCOMPWZ Events by Alert Status and Deployment Year and Month

4.4.1.1 Observed SPDCOMPWZ Events by Treatment Group

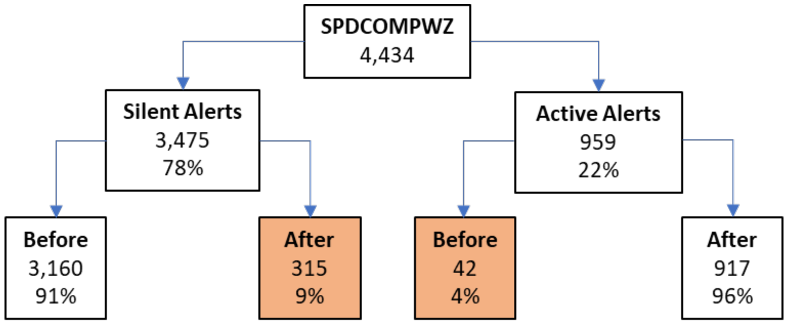
The treatment group received 4,434 SPDCOMPWZ events (95% of all SPDCOMPWZ events). There were 3,475 silent and 959 active SPDCOMPWZ events (78% and 22%, respectively, of treatment group SPDCOMPWZ events). Figure 49 illustrates the breakdown of silent and active SPDCOMPWZ events for the treatment group by month during the yearlong deployment.



Source: U.S DOT Volpe Center

Figure 49. Distribution of Treatment Group SPDCOMPWZ Events by Alert Status and Deployment Year and Month

The before period contained 3,202 treatment group SPDCOMPWZ events (72%). The after period contained 1,232 treatment group SPDCOMPWZ events (28%). Figure 50 breaks down the silent and active alerts by the before and after periods.

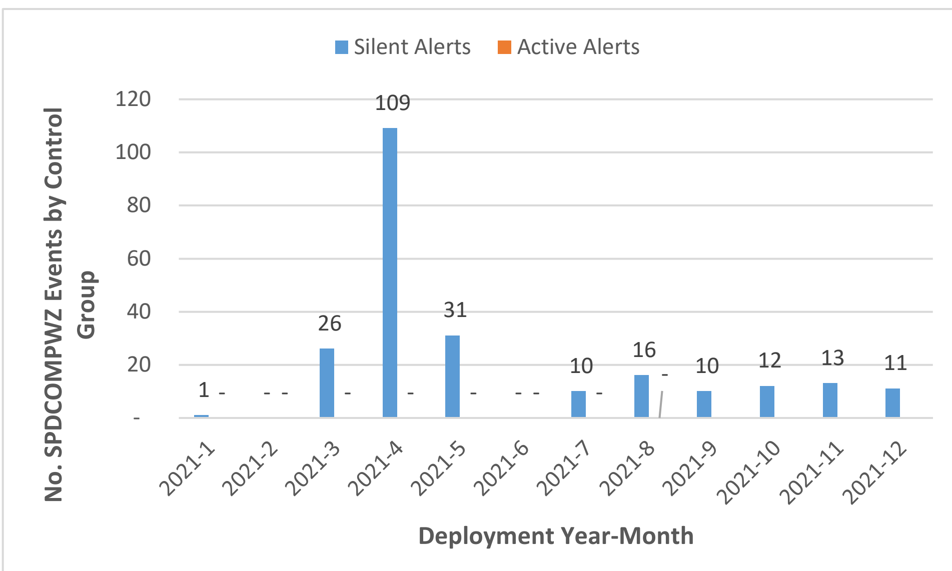


Source: U.S DOT Volpe Center

Figure 50. Breakdown of Treatment Group SPDCOMPWZ Events by Alert Status and Deployment Period

4.4.1.2 SPDCOMPWZ Events Observed by Control Group

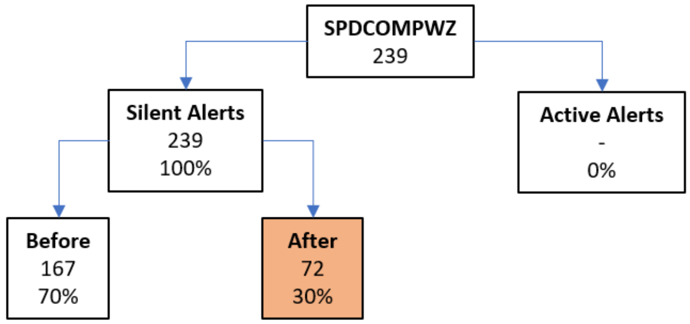
The control group experienced 239 SPDCOMPWZ events (5% of all SPDCOMPWZ events). These events comprised 239 silent SPDCOMPWZ events (100%) and no active SPDCOMPWZ events. Figure 51 illustrates the breakdown of silent SPDCOMPWZ events for the control group by month during the yearlong deployment period.



Source: U.S DOT Volpe Center

Figure 51. Distribution of Control Group SPDCOMPWZ Events by Alert Status and Deployment Year and Month

The before period contained 167 control group SPDCOMPWZ events (70%). The after period contained 72 control group SPDCOMPWZ events (30%). Figure 52 breaks down the number of silent and active alerts by the before and after periods.



Source: U.S DOT Volpe Center

Figure 52. Breakdown of Control Group SPDCOMPWZ Events by Alert Status and Deployment Period

4.4.2 Data Filtering of SPDCOMPWZ Events

The Volpe team removed SPDCOMPWZ events from the analysis due to data and alert validity issues.

4.4.2.1 SPDCOMPWZ Events with Data Issues

The Volpe team removed some SPDCOMPWZ events from the analysis due to data collection and processing issues, including:

1. The pre-warning or post-warning recording times were insufficient.
2. Alerts were triggered above the speed limit threshold (i.e., excessiveZoneSpd parameter was greater than 0).
3. The HV speed was unrealistic or erroneous (i.e., greater than 24.6 m/s or 55 mph).
4. Events contained less than three seconds of x-y data after the alert.

Table 41 indicates the number of discarded SPDCOMPWZ events for the filtering conditions listed above. Filtering was applied independently of the control and treatment groups, silent and active alerts, and before and after periods. The filtering process removed 78 SPDCOMPWZ events (1.7%) of all SPDCOMPWZ events. The Volpe team deemed the remaining 4,595 SPDCOMPWZ events to be acceptable for further analysis.

Table 41. Filtering Results of SPDCOMPWZ Events with Data Issues

Data Quality	Count	Percentage
Insufficient pre- or post-warning times	3	0.1%
Speed > 24.6 m/s (55 mph)	26	0.6%
Insufficient Data after Alert	49	1.0%
Good Data	4,595	98.3%
Total	4,673	100.0%

4.4.2.2 SPDCOMPWZ Events with Invalid Alerts

The Volpe team removed SPDCOMPWZ events from the analysis that were deemed to have experienced invalid alerts due to limitations in application capability, including:

1. The HV speed at alert onset was below the minimum speed threshold of 11.2 m/s (25 mph).

The Volpe team was unable to identify SPDCOMPWZ events occurring in areas that did not contain any instrumented locations.

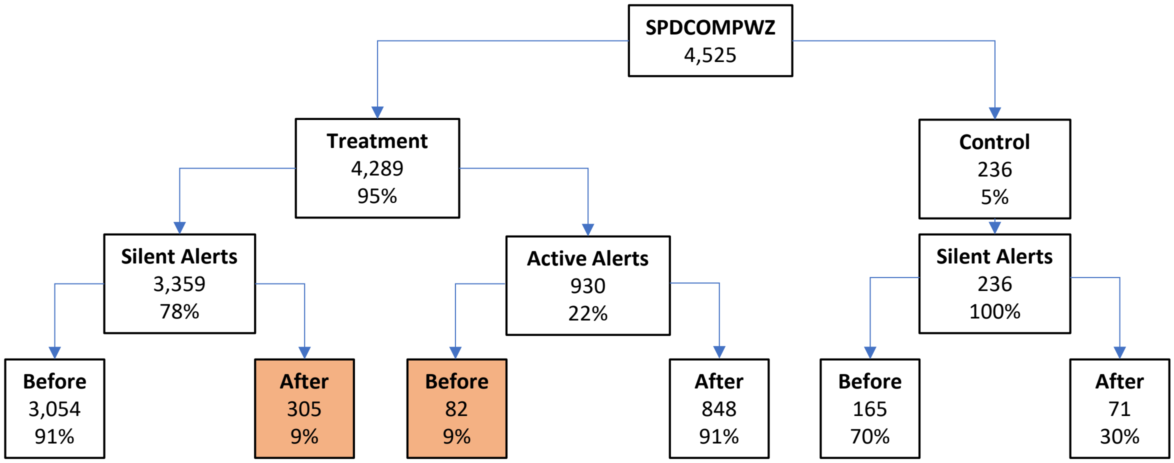
Table 42 indicates the number of discarded SPDCOMPWZ events for the filtering condition listed above. Filtering was applied independently of the control and treatment groups, silent and active alerts, and before and after periods. The filtering process removed 70 invalid SPDCOMPWZ events (98.5% of the acceptable SPDCOMPWZ events), yielding 4,525 valid SPDCOMPWZ events for further analysis.

Table 42. Filtering Results of SPDCOMPWZ Events with Invalid Alerts

Alert Validity	**Count**	**Percentage**
Speed < 11.2 m/s (25 mph)	70	1.5%
Valid	4,525	98.5%
Total	4,595	100.0%

4.4.2.3 SPDCOMPWZ Events with Valid Alerts

Data filtering of SPDCOMPWZ events resulted in a total of 4,525 events (96.8% of all observed SPDCOMPWZ events). The treatment group experienced 4,289 of these events. Figure 53 illustrates the breakdown of valid SPDCOMPWZ events by treatment and control groups, silent and active alerts, and before and after periods. The treatment group erroneously received 305 silent alerts in the after period and 82 active alerts in the before period (red cells in Figure 53). These events represent 9% of all treatment group SPDCOMPWZ events with valid alerts. These alerts, while valid, would generally be excluded from the safety impact analysis. The safety impact analysis normally compares the performance of the treatment group in the before period (with appropriately silent alerts) to the after period (with appropriately active alerts).



Source: U.S DOT Volpe Center

Figure 53. Breakdown of Valid SPDCOMPWZ Treatment and Control Group Events by Alert Status and Deployment Period

The Volpe team decided to assess the safety impact of SPDCOMPWZ by comparing the vehicle/driver response between all 3,595 valid silent alerts and all 930 valid active alerts, regardless of period (before or after) or vehicle group (treatment or control).

4.4.3 Analysis of Valid SPDCOMPWZ Events

The data validation process yielded 4,525 SPDCOMPWZ events with valid alerts for further analysis. SPDCOMPWZ events with silent and active alerts accounted respectively for 79% and 21% of all these events.

4.4.3.1 Initial Conditions of Valid SPDCOMPWZ Events

The Volpe team used the HV travel speed at alert onset as a single measure of performance to characterize initial vehicle conditions at the time of alert onset for SPDCOMPWZ events. Table 43 presents the descriptive statistics of HV speed at alert onset in SPDCOMPWZ events, and the result of the two-sample two-tailed student's t-Test on data sets with unequal variances between silent and active alert events. The difference in the mean of $V_{HV}(0)$ between silent and active alert events is not statistically significant.

Table 43. Descriptive Statistics and Statistical Test Results of HV Speed at Alert Onset (m/s) in Valid SPDCOMPWZ Events by Alert Status

Alert Status	Count	Mean	StdDev	Minimum	Median	Maximum	$P(T \leq t)$
Silent	3,595	7.54	1.48	4.48	6.78	14.96	0.256
Active	930	7.61	1.48	6.68	6.85	17.16	

4.4.3.2 *Vehicle/Driver Response to Valid SPDCOMPWZ Events*

The Volpe team analyzed the following two measures of performance for vehicle/driver response to SPDCOMPWZ events:

1. $V_{HV}(min)$ m/s
2. $\Delta V_{HV}(min)$ m/s

Table 44 presents the descriptive statistics of these two measures in SPDCOMPWZ events, and the results of the two-sample two-tailed student's t-Test on data sets with unequal variances between silent and active alert events. Events with silent alerts experienced slightly smaller minimum travel speed after alert onset (5.6 m/s) than events with active alerts (5.8 m/s). The HV minimum speed differential after alert onset was larger in events with silent alerts (2.0 m/s) than in events with active alerts (1.8 m/s). These two results are statistically significant at the 97% and 90% confidence levels, respectively. The difference in both measures of performance is only 0.2 m/s (0.45 mph) or less, which is practically insignificant.

Table 44. Descriptive Statistics and Statistical Test Results of $V_{HV}(min)$ and $\Delta V_{HV}(min)$ in Valid SPDCOMPWZ Events by Alert Status

Response Measure	Alert Status	Count	Mean	StdDev	Minimum	Median	Maximum	P(T≤t)
$V_{HV}(min)$ m/s	Silent	3,595	5.58	2.70	0	6.68	13.74	0.03
	Active	930	5.79	2.67	0	6.68	17.16	
$\Delta V_{HV}(min)$ m/s	Silent	3,595	1.96	2.66	0	0.42	12.94	0.10
	Active	930	1.81	2.32	0	0.62	10.12	

4.4.4 SPDCOMPWZ Safety Effectiveness

The Volpe team did not observe any safety effectiveness of the advisory SPDCOMPWZ application based on selected measures of performance.

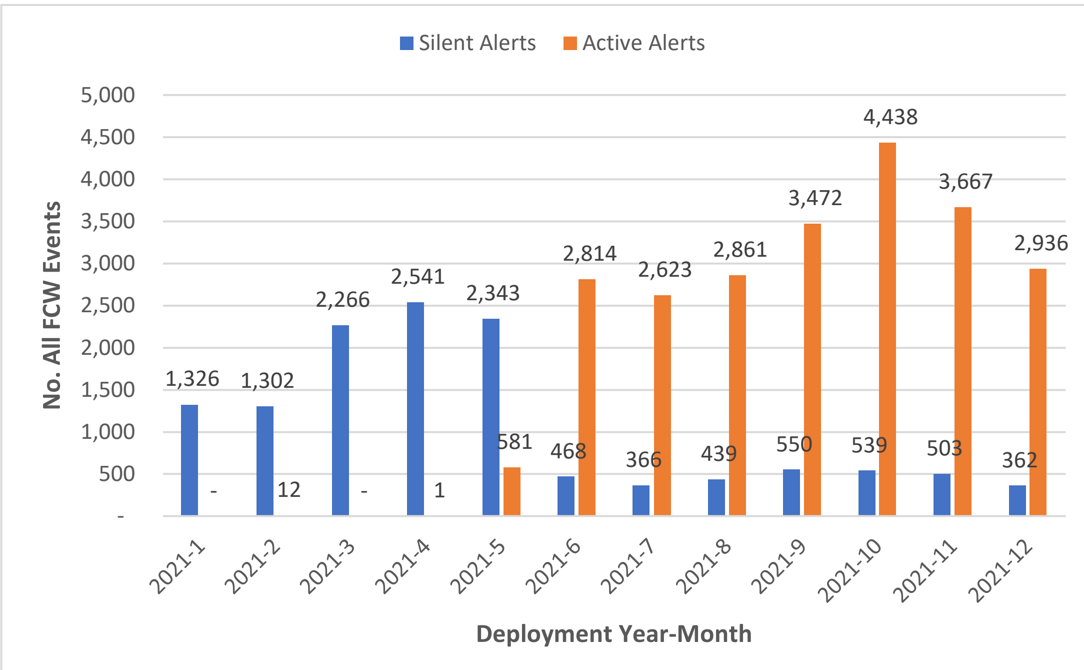
5 Analysis of V2V Alert Events and Driver Response

This section presents the results of applying the steps of the safety impact assessment approach to each of the following five V2V safety applications: FCW, EEBL, LCW, BSW, and IMA.

5.1 Forward Crash Warning

5.1.1 Observed FCW Events

The SDC contained 36,410 FCW events from the NYC CVP deployment. These events comprised 13,005 FCW events with silent alerts (36%) and 23,405 FCW events with active alerts (64%). Figure 54 illustrates the breakdown of FCW events with silent and active alerts by month during the yearlong deployment. In the before period, there were 9,791 FCW events (27%). In the after period, there were 26,619 FCW events (73%).

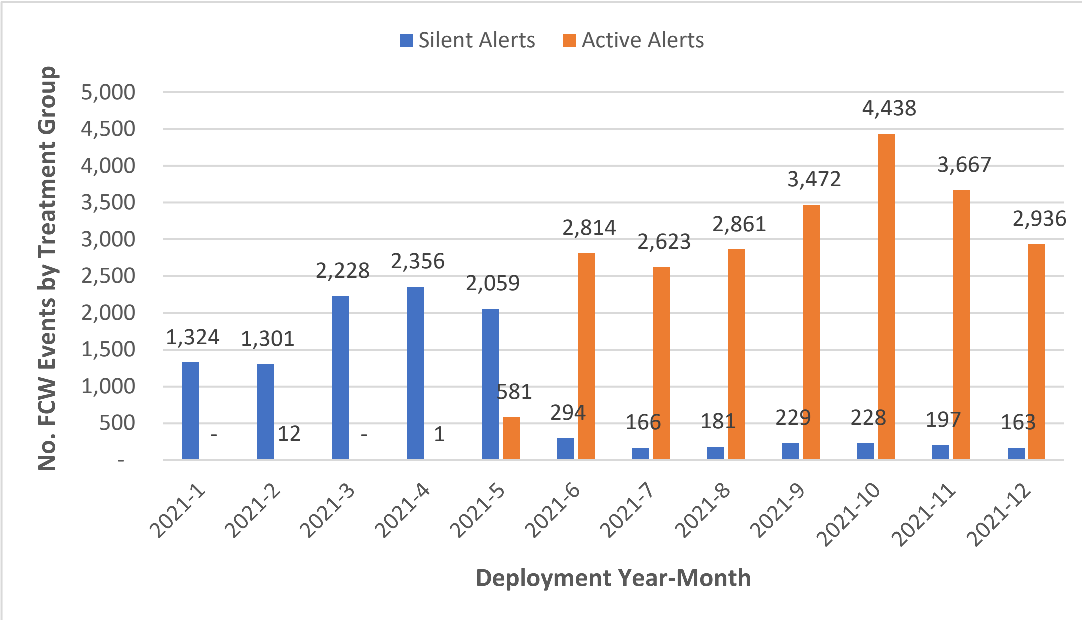


Source: U.S DOT Volpe Center

Figure 54. Distribution of All FCW Events by Alert Status and Deployment Year and Month

5.1.1.1 Observed FCW Events by Treatment Group

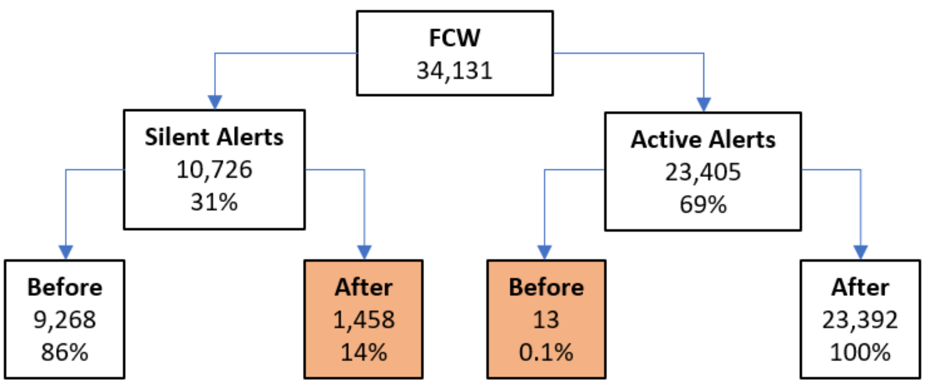
The treatment vehicle group received 34,131 FCW events (94% of all FCW events). There were 10,726 silent and 23,405 active FCW events (31% and 69%, respectively, of treatment group FCW events). Figure 55 illustrates the breakdown of FCW events with silent and active alerts for the treatment group by month during the yearlong deployment.



Source: U.S DOT Volpe Center

Figure 55. Distribution of Treatment Group FCW Events by Alert Status and Deployment Year-Month

The before period contained 9,281 treatment group FCW events (27%). The after period contained 24,850 treatment group FCW events (73%). Figure 56 breaks down the FCW events by silent and active alerts by the before and after periods.



Source: U.S DOT Volpe Center

Figure 56. Breakdown of Treatment Group FCW Events by Alert Status and Deployment Period

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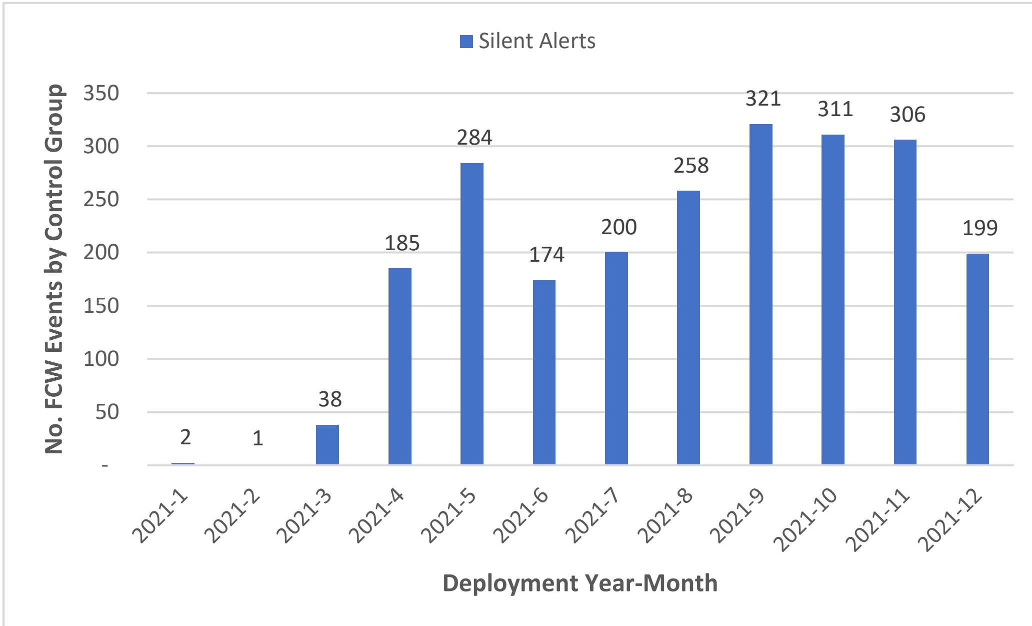
5.1.1.2 FCW Events Observed by Control Group

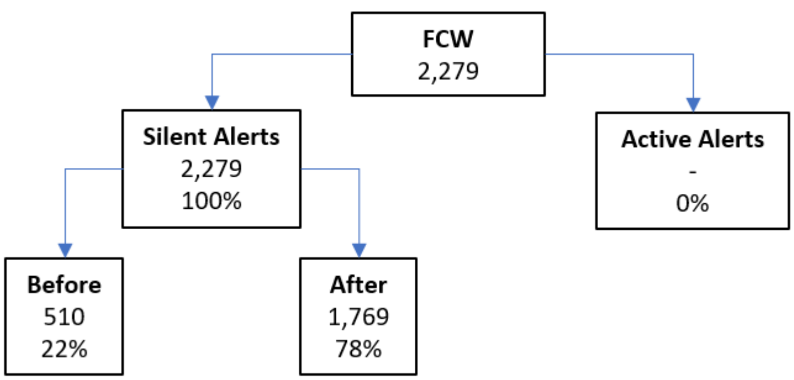
The control group experienced 2,279 FCW events (6% of all FCW events). These events comprised 2,279 FCW events with silent alerts (100%) and no FCW events with active alerts. Figure 57 illustrates the breakdown of FCW events with silent and active alerts for the control group by month during the yearlong deployment.



Source: U.S DOT Volpe Center

Figure 57. Distribution of Control Group FCW Events by Alert Status and Deployment Year and Month

The before period contained 510 control group FCW events (22%). The after period contained 1,769 control group FCW events (78%). Figure 58 breaks down the number of silent and active alerts by the before and after periods.



Source: U.S DOT Volpe Center

Figure 58. Breakdown of Control Group FCW Events by Alert Status and Deployment Period

5.1.2 Data Filtering of FCW Events

The Volpe team removed FCW events from the analysis due to data and alert validity issues.

5.1.2.1 FCW Events with Data Issues

The Volpe team removed FCW events from the analysis due to data collection and processing issues, including:

1. The pre-warning or post-warning recording times were insufficient.
2. The trajectory of the HV or RV was discontinuous or unreasonable.

3. The HV or RV did not have range or relative position data (i.e., the obfuscated GPS data was missing).
4. The HV or RV speed was unrealistic or erroneous (i.e., greater than 55 mph).
5. The x-y coordinates of the HV or RV indicated it was stationary while its speed was non-zero.

Table 45 indicates the number of discarded FCW events for each filtering condition listed above. Filtering was applied independently of the control and treatment groups, silent and active alerts, and before and after periods. The filtering process removed 19,232 FCW events (53%) of all FCW events. The Volpe team deemed the remaining 17,178 FCW events to be acceptable for further analysis.

Table 45. Filtering Results of FCW Events with Data Issues

Data Quality	Count	Percentage
Insufficient pre- or post-warning times	223	0.6%
Unreasonable Vehicle Trajectory	132	0.4%
Missing or Insufficient X-Y Data	14,210	39.0%
Speed > 24.6 m/s (55 mph)	4,281	11.8%
Incorrect X-Y Conversion	386	1.1%
Good Data	**17,178**	47.2%
Total	**36,410**	100.0%

5.1.2.2 FCW Events with Invalid Alerts

The Volpe team removed FCW events from the analysis that were deemed to have experienced invalid alerts due to limitations in application capability, including:

1. There was a substantial elevation difference between the HV and RV (based on a minimum vertical clearance for a bridge over a roadway, at least 32.8 feet (10 m)).
2. The RV was not in the forward path (i.e., same lane) of the HV.
3. The HV appeared to pass through the RV after the alert was issued.
4. The HV and RV were separating at alert onset (range increasing at a rate greater than 0.5 m/s).
5. The RV was significantly far away from the HV at alert onset (greater than 120 m (394 ft)).
6. If the HV speed at alert onset was below 1.1 m/s.

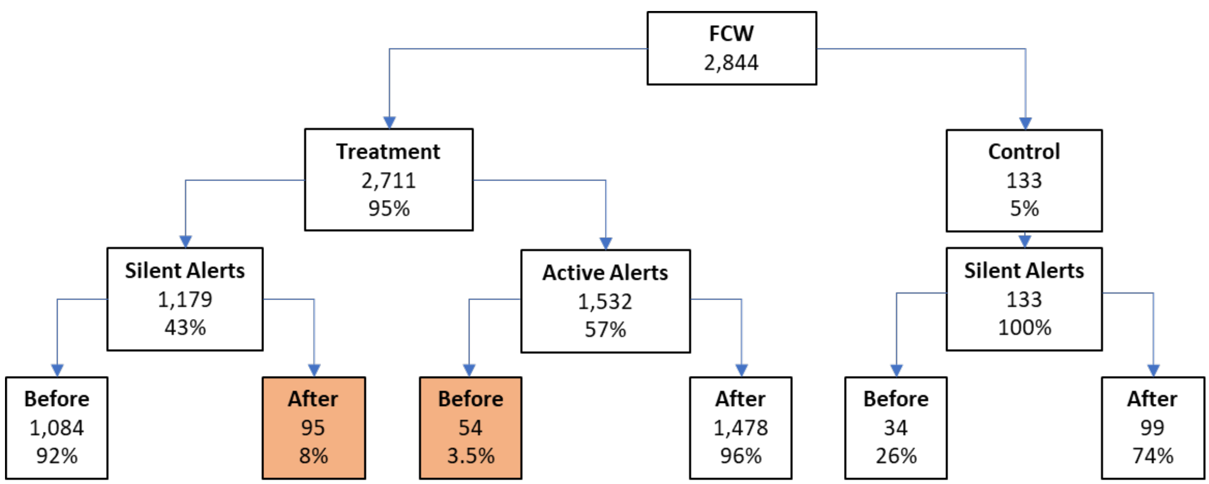
Table 46 indicates the number of discarded FCW events for each filtering condition listed above. Filtering was applied independently of the control and treatment groups, silent and active alerts, and before and after periods. The filtering process removed 14,334 invalid FCW events (83% of the acceptable FCW events). The Volpe team assessed the safety impact of the FCW application based on the remaining 2,844 FCW events that were deemed to be valid.

Table 46. Filtering of FCW Events with Invalid Alerts

Alert Validity	Count	Percentage
Elevation discrepancy	1,208	7.0%
RV not in same lane as HV	6,304	36.7%
HV passes through the RV after alert	5,996	34.9%
Vehicles separating at alert onset	768	4.5%
RV far away (> 120 m)	58	0.3%
HV speed below 1.1 m/s	0	0%
Valid	**2,844**	16.6%
Total	17,178	100.0%

5.1.2.3 FCW Events with Valid Alerts

The filtering of the data yielded 2,844 FCW events with valid alerts (8% of all observed FCW events). Figure 59 illustrates the breakdown of these events by treatment and control groups, silent and active alerts, and before and after periods.



Source: U.S DOT Volpe Center

Figure 59. Breakdown of Valid Treatment and Control Group FCW Events by Alert Status and Deployment Period

The treatment group erroneously received 95 silent alerts in the after period and 54 active alerts in the before period (red cells in Figure 59), totaling 149 events or 5% of all treatment group FCW events with valid alerts. These events represent 149 alerts or 5% of all treatment group FCW events with valid alerts. These alerts, while valid, would generally be excluded from the safety impact analysis. The safety impact analysis normally compares the performance of the treatment group in the before period (with appropriately silent alerts) to the after period (with appropriately active alerts).

5.1.3 Valid FCW Data Analysis

The treatment group had 1,084 valid FCW events with silent alerts in the before period and 1,478 of such events with active alerts in the after period, accounting respectively for 42% and 58% of all appropriate valid FCW alerts (Figure 68). Overall, the data filtering process resulted in a total of 2,844 valid FCW events that included 1,312 (46%) events with silent alerts and 1,532 (54%) events with active alerts. Consequently, the Volpe team decided to assess the safety impact of FCW by comparing the response between all silent and all active alerts from both the treatment and control groups due to the larger sample size.

5.1.3.1 Breakdown of FCW Event Scenarios

The Volpe team divided FCW events by the following three dynamically-distinct scenarios at alert onset:

1. Lead vehicle stopped (LVS): HV is going straight and then closes in on a stopped lead vehicle (RV).
2. Lead vehicle moving at constant speed (LVM): HV is going straight and then closes in on a lead vehicle moving at a lower constant speed.
3. Lead vehicle decelerating (LVD): HV is going straight while following a lead vehicle and then the lead vehicle decelerates.

Table 47 shows the breakdown of all valid FCW events with silent and active alerts by scenario. The 'other' scenarios include the lead vehicle accelerating and other dynamic state combinations of the HV and RV.

Table 47. Breakdown of Valid FCW Events by Scenario and Alert Status

FCW Scenario	Silent Alerts	Active Alerts	Total	Silent Alerts	Active Alerts	Total
LVS	180	142	322	13.7%	9.3%	11.3%
LVM	436	696	1,132	33.2%	45.4%	39.8%
LVD	608	554	1,162	46.3%	36.2%	40.9%
Other	88	140	228	6.7%	9.1%	8.0%
Total	1,312	1,532	**2,844**	100.0%	100.0%	100.0%

Excluding the 228 'other' events, the LVD and LVM scenarios accounted respectively for about 44% and 43% of the remaining 2,616 valid FCW events. The LVS scenario accounted for only 12% of these events. Consequently, the Volpe team decided to merge the LVS scenario with the LVM scenario and create the LVSM scenario for further analysis. This merger is justified since both scenarios present the same optical flow (constant range rate), defined as the the pattern of apparent motion of objects in a visual scene caused by the relative motion between an observer and a scene. On the other hand, the LVD scenario presents a different optical flow that varies with time (non-constant range rate). The optical flow influences driver's assessment of the time to collision and their response to the obstacle in their path. Table 48 shows the breakdown of all valid FCW events with silent and active alerts by LVSM and LVD scenarios. The LVSM scenario accounted for 1,454 valid FCW events with 616 silent alerts (42.4%) and 838 active alerts (57.6%). On the other hand, the LVD scenario accounted for 1,162 valid FCW events with 608 silent alerts (52.3%) and 554 active alerts (47.7%).

Table 48. Breakdown of Valid FCW Events by LVSM and LVD Scenarios and Alert Status

FCW Scenario	Silent Alerts	Active Alerts	Total	Silent Alerts	Active Alerts	Total
LVSM	616	838	1,454	50.3%	60.2%	55.6%
LVD	608	554	1,162	49.7%	39.8%	44.4%
Total	1,224	1,392	**2,616**	100.0%	100.0%	100.0%

5.1.3.2 Initial Conditions of FCW Scenario Events

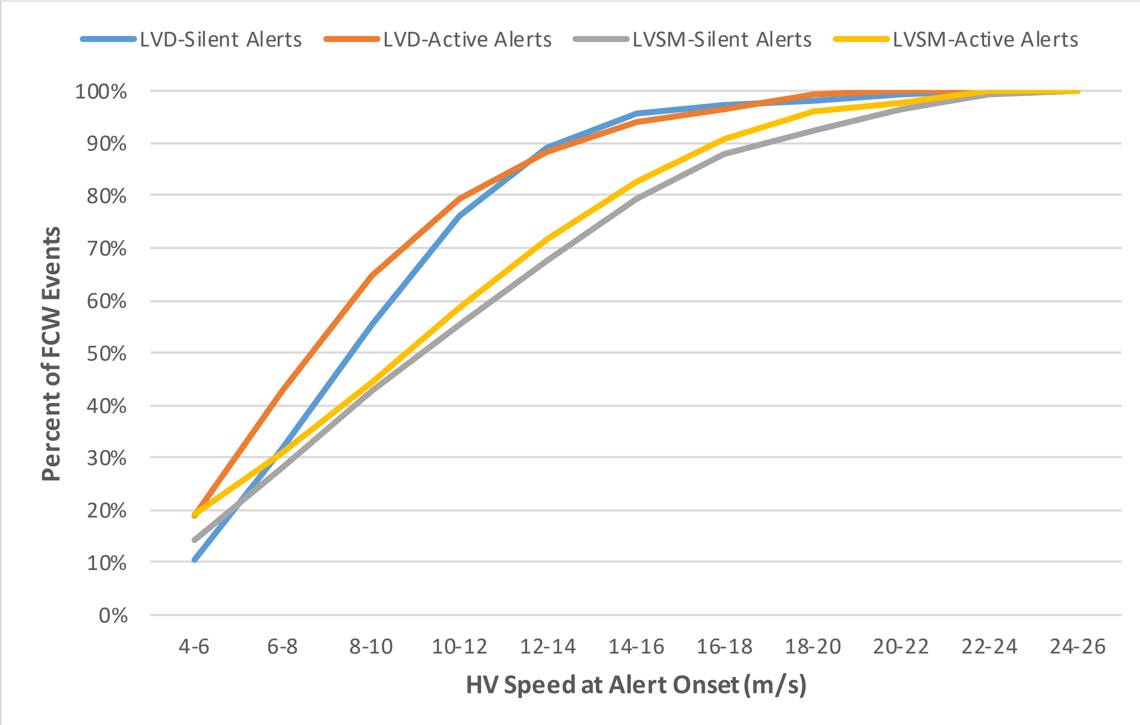
The Volpe team analyzed the following measures of performance for the initial conditions of FCW scenarios:

1. $V_{HV}(0)$ (m/s)
2. Time to collision at alert onset (s) ≡ TTC(0)

Table 49 presents the descriptive statistics of $V_{HV}(0)$ in the two FCW scenarios, and the results of the two-tailed t-Tests on data sets with unequal variances between silent and active alert events. The difference in the mean of HV travel speed at alert onset of about 0.6 m/s (1.3 mph) is statistically significant between events with silent and active alerts in each of the two FCW scenarios. Figure 70 shows that about 90% of LVD and LVSM events occurred respectively at speeds below 14 m/s (31.3 mph) and 18 m/s (40.3 mph). In the LVD scenario, about 32% of events with silent alerts occurred below 8 m/s (17.9 mph) as opposed to about 43% of events with active alerts. In the LVSM scenario, about 68% of events with silent alerts occurred below 14 m/s (31.3 mph) as opposed to about 72% of events with active alerts.

Table 49. Descriptive Statistics and Statistical Test Results of $V_{HV}(0)$ in Valid FCW Scenario Events by Alert Status

FCW Scenario	Alert Status	Count	Mean	StdDev	Minimum	Median	Maximum	$P(T \leq t)$
LVSM	Silent	616	11.78	4.98	4.4	11.1	24.28	< 0.05
	Active	838	11.14	4.71	4.18	10.93	23.54	
LVD	Silent	608	9.91	3.38	4.36	9.56	23.34	< 0.05
	Active	554	9.28	3.61	4.14	8.53	21.74	



Source: U.S DOT Volpe Center

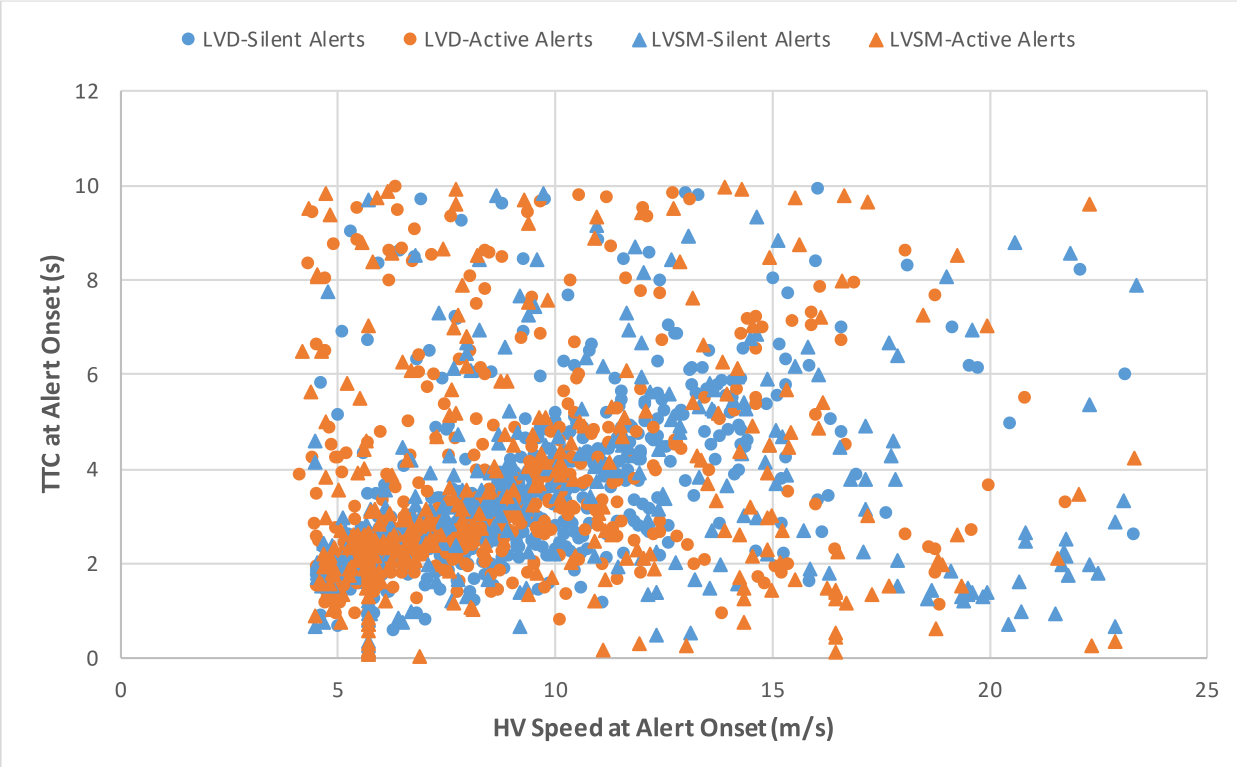
Figure 60. Cumulative Distributions of FCW Events by Scenario and Alert Status as Function of HV Travel Speed at Alert Onset

Table 50 presents the descriptive statistics of TTC(0) in the two FCW scenarios, and the results of the two-tailed t-Tests on data sets with unequal variances between silent and active alert events. The Volpe team excluded from this analysis any event that had TTC(0) over 10 s, assuming the FCW alert was issued too soon. There is no statistically-significant difference in the mean values of TTC(0) of both scenarios between events with silent and active alerts. The results of this key initial condition imply that vehicle/driver response can be reliably compared between events with silent and active alerts.

Table 50. Descriptive Statistics and Statistical Test Results of TTC(0) in Valid FCW Scenario Events by Alert Status

FCW Scenario	Alert Status	Count	Mean	StdDev	Minimum	Median	Maximum	P(T ≤ t)
LVSM	Silent	504	3.61	1.76	0.59	3.11	9.91	0.83
	Active	419	3.64	2.11	0.81	2.93	9.96	
LVD	Silent	310	3.51	2.10	0.07	3.16	9.84	0.52
	Active	301	3.63	2.50	0.05	2.71	9.94	

Figure 61 illustrates the similarities of the initial condition pairs between events with silent and active alerts for both FCW scenarios.



Source: U.S DOT Volpe Center

Figure 61. Scatter Plots of TTC(0) vs. $V_{HV}(0)$ for FCW Scenario Events with Silent and Active Alerts

5.1.3.3 Vehicle/Driver Response to FCW Scenario Events

The Volpe team analyzed the following measures of performance for vehicle/driver response to FCW alerts:

1. Minimum time to collision after alert onset (s) ≡ TTCmin
2. Minimum time headway after alert onset (s) ≡ THmin

Table 51 presents the descriptive statistics of TTCmin in the two FCW scenarios, and the results of the two-tailed t-Tests on data sets with unequal variances between silent and active alert events. The Volpe team excluded from this analysis any TTCmin value over 10 s to avoid including outliers. Moreover, the Volpe team was not able to calculate this measure in some cases due to insufficient data. Therefore, the counts in Table 51 are lower than the total counts of valid FCW events in each category. Statistical test results did not yield any significant differences in the mean TTCmin between events with silent and active alerts in both scenarios.

Table 51. Descriptive Statistics and Statistical Test Results of TTCmin (s) in Valid FCW Scenario Events by Alert Status

FCW Scenario	Alert Status	Count	Mean	StdDev	Minimum	Median	Maximum	P(T ≤ t)
LVSM	Silent	485	3.19	2.29	0.04	2.54	9.94	
	Active	605	3.40	2.40	0.04	2.67	10.00	0.144
LVD	Silent	583	2.56	1.61	0.14	2.08	9.98	
	Active	532	2.69	1.88	0.11	2.05	9.98	0.247

Table 52 presents the descriptive statistics of THmin in the two FCW scenarios, and the results of the two-tailed t-Tests on data sets with unequal variances between silent and active alert events. The Volpe team did not filter out any values of this measure from the analysis. The difference in the mean of THmin of about 0.2 s is statistically significant between events with silent and active alerts in each of the two FCW scenarios.

Table 52. Descriptive Statistics and Statistical Test Results of THmin (s) in Valid FCW Scenario Events by Alert Status

FCW Scenario	Alert Status	Count	Mean	StdDev	Minimum	Median	Maximum	P(T ≤ t)
LVSM	Silent	616	2.28	1.18	0.28	2.13	7.10	
	Active	838	2.05	1.01	0.27	1.76	6.84	<< 0.05
LVD	Silent	608	2.53	0.99	0.60	2.43	6.61	
	Active	554	2.28	0.94	0.47	2.19	7.43	<< 0.05

5.1.3.4 Analysis of FCW Events with Brake Response

The Volpe team also analyzed FCW events that prompted brake application after alert onset, excluding events without a brake response or a brake response with zero brake reaction time (the brake was already applied at alert onset). Table 53 shows the breakdown of all 911 valid FCW events with silent and active alerts by LVSM and LVD scenarios, which experienced brake application after alert onset. The LVSM scenario accounted for 218 valid FCW events with 114 silent alerts (52.3%) and 104 active alerts (47.7%). On the other hand, the LVD scenario accounted for 693 valid FCW events with 390 silent alerts (56.3%) and 303 active alerts (43.7%).

Table 53. Breakdown of Valid FCW Events with Brake Response by LVSM and LVD Scenarios and Alert Status

FCW Scenario	Silent Alerts	Active Alerts	Total	Silent Alerts	Active Alerts	Total
LVSM	114	104	218	23%	25%	24%
LVD	390	303	693	77%	73%	75%
Total	504	407	**911**	99.6%	98.5%	99.1%

5.1.3.4.1 Initial Conditions of FCW Events with Brake Response

Table 54 and Table 55 present the descriptive statistics respectively of VHV(0) and TTC(0) in the two FCW scenarios, and the results of the two-tailed t-Tests on data sets with unequal variances between silent and active alert events. The difference in the mean of $V_{HV}(0)$ of about 0.6 m/s (1.3 mph) in the LVSM scenario is statistically significant between events with silent and active alerts. This difference is not statistically significant in the LVD scenario. In contrast, the difference in the mean of TTC(0) of about 0.1 s in the LVD scenario, and not in the LVSM scenario, is statistically significant between events with silent and active alerts.

Table 54. Descriptive Statistics and Statistical Test Results of $V_{HV}(0)$ in Valid FCW Scenario Events with Brake Response by Alert Status

FCW Scenario	Alert Status	Count	Mean	StdDev	Minimum	Median	Maximum	P(T ≤ t)
LVSM	Silent	390	9.72	3.15	4.54	9.49	23.34	
	Active	303	9.11	3.49	4.14	8.4	21.74	0.0179
LVD	Silent	114	9.29	3.77	4.5	8.7	21.56	
	Active	104	9.80	3.84	4.44	9.43	19.22	0.3281

Table 55. Descriptive Statistics and Statistical Test Results of TTC(0) in Valid FCW Scenario Events with Brake Response by Alert Status

FCW Scenario	Alert Status	Count	Mean	StdDev	Minimum	Median	Maximum	P(T ≤ t)
LVSM	Silent	372	3.50	1.56	0.91	3.06	9.91	
	Active	263	3.23	1.62	0.81	2.81	9.71	0.7056
LVD	Silent	105	3.55	1.50	0.65	3.29	7.67	
	Active	73	3.64	1.74	0.89	3.20	9.51	< 0.05

5.1.3.4.2 Vehicle/Driver Response in FCW Events with Brake Response

The Volpe team analyzed the following measures of performance for vehicle/driver braking response to FCW alerts:

1. TTCmin (s)
2. THmin (s)
3. A_{HV} (m/s^2)
4. Ap_{HV} (m/s^2)
5. BRT (s)

Table 56 and Table 57 present the descriptive statistics of above response measures, and the results of the two-tailed t-Tests on data sets with unequal variances between silent and active alert events, respectively in the LVSM and LVD scenarios. The Volpe team excluded from this analysis any TTCmin value over 10 s and zero BRT. In the LVSM scenario, statistical test results did not yield any significant differences in the mean of the five measures between events with silent and active alerts. In contrast, the LVD scenario events experienced statistically-significant differences in the mean of THmin at over the 95% confidence level (≈ 0.2 s greater with silent alerts) and in the mean of A_{HV} (≈ 0.1 m/s² less with active alerts), Ap_{HV} (≈ 0.1 m/s² less with active alerts), and BRT (≈ 0.1 s less with active alerts) at over the 90% confidence level.

Table 56. Descriptive Statistics and Statistical Test Results of Response Measures in Valid FCW LVSM Scenario Events with Brake Response by Alert Status

Response Measure	Alert Status	Count	Mean	StdDev	Minimum	Median	Maximum	P(T ≤ t)
TTCmin (s)	Silent	113	2.40	1.46	0.31	1.95	8.67	0.112
	Active	100	2.74	1.68	0.16	2.25	9.26	
THmin (s)	Silent	113	2.83	0.88	0.28	2.83	5.12	0.104
	Active	100	2.61	1.06	0.81	2.66	5.60	
A_{HV} (m/s²)	Silent	60	-1.96	0.39	-2.56	-2.07	-0.56	0.632
	Active	49	-1.92	0.50	-3.65	-2.06	-0.82	
Ap_{HV} (m/s²)	Silent	60	-2.29	0.24	-3.27	-2.28	-2.00	0.458
	Active	49	-2.34	0.35	-4.10	-2.24	-2.00	
BRT (s)	Silent	113	1.94	1.32	0.20	1.60	4.90	0.634
	Active	100	2.03	1.29	0.10	1.75	5.00	

Table 57. Descriptive Statistics and Statistical Test Results of Response Measures in Valid FCW LVD Scenario Events with Brake Response by Alert Status

Response Measure	Alert Status	Count	Mean	StdDev	Minimum	Median	Maximum	P(T ≤ t)
TTCmin (s)	Silent	385	2.14	1.01	0.20	1.91	8.13	0.210
	Active	302	2.27	1.43	0.17	1.93	9.85	
THmin (s)	Silent	385	2.41	0.79	0.60	2.36	5.40	< 0.05
	Active	302	2.25	0.75	0.47	2.23	5.81	
A_{HV} (m/s²)	Silent	225	-2.33	0.47	-4.18	-2.26	-0.78	0.078
	Active	191	-2.25	0.41	-3.51	-2.23	0.00	
Ap_{HV} (m/s²)	Silent	225	-2.68	0.59	-5.24	-2.53	-2.00	0.092
	Active	191	-2.59	0.50	-5.15	-2.51	-2.00	
BRT (s)	Silent	385	1.21	0.97	0.10	0.90	4.80	0.076
	Active	302	1.08	0.90	0.10	0.80	4.80	

In addition to the five response measures of performance listed above, the Volpe team also examined another measure that captured the number of encounters with rear-end near crashes. The Volpe team defined this measure as any braking response to an FCW event that resulted in a TTCmin less than or equal to 3 s AND A_{HV} < -2.45 m/s² (0.25 g). Table 58 shows the results of the near-crash analysis, with only four near crashes observed in the LVSM scenario (≈ 0% of all LVSM events) and 150 near crashes in the LVD scenario (≈ 13% of all LVD events). In the latter scenario, near crashes accounted for about 15% of FCW events with silent alerts compared to 11% of such events with active alerts. This difference in the ratio of near crashes in the LVD scenario is statistically significant at over the 93% confidence level between events with silent and active alerts, based on the odds ratio test with P value of 0.066.

Table 58. Near-Crash Results of FCW Events by Scenario and Alert Status

FCW Scenario	Alert Status	Not Near Crash	Near Crash	Total	Percent Not Near Crash	Percent Near Crash
LVSM	Silent	615	1	616	99.8%	0.2%
	Active	835	3	838	99.6%	0.4%
	Total	1,450	4	1,454	99.7%	0.3%
LVD	Silent	519	89	608	85.4%	14.6%
	Active	493	61	554	89.0%	11.0%
	Total	1,012	150	1,162	87.1%	12.9%

5.1.4 FCW Safety Effectiveness

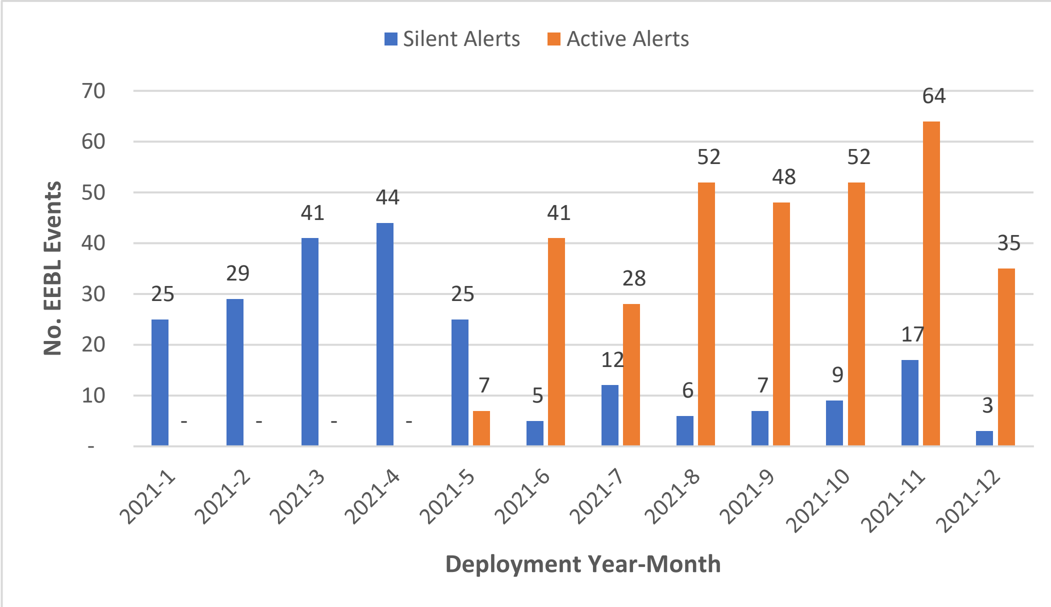
The analysis of the safety impact of FCW on vehicle/driver response revealed effectiveness in reducing brake reaction time from 1.21 s in LVD events with silent alerts to 1.08 s in LVD events with active alerts. There was a slight reduction in average deceleration in LVD events from 2.33 m/s^2 with silent alerts to 2.25 m/s^2 with active alerts.

FCW was 25% effective in reducing LVD near-crash rates from 14.6% with silent alerts to 11.0% with active alerts.

5.2 Electronic Emergency Brake light

5.2.1 Observed EEBL Events

The SDC contained 550 EEBL events from the NYC CVP deployment. These events comprised 223 silent EEBL events (41%) and 327 active EEBL events (59%). Figure 62 illustrates the breakdown of silent and active EEBL events by month during the yearlong deployment. In the before period, there were 164 EEBL events (30%). In the after period, there were 386 EEBL events (70%).

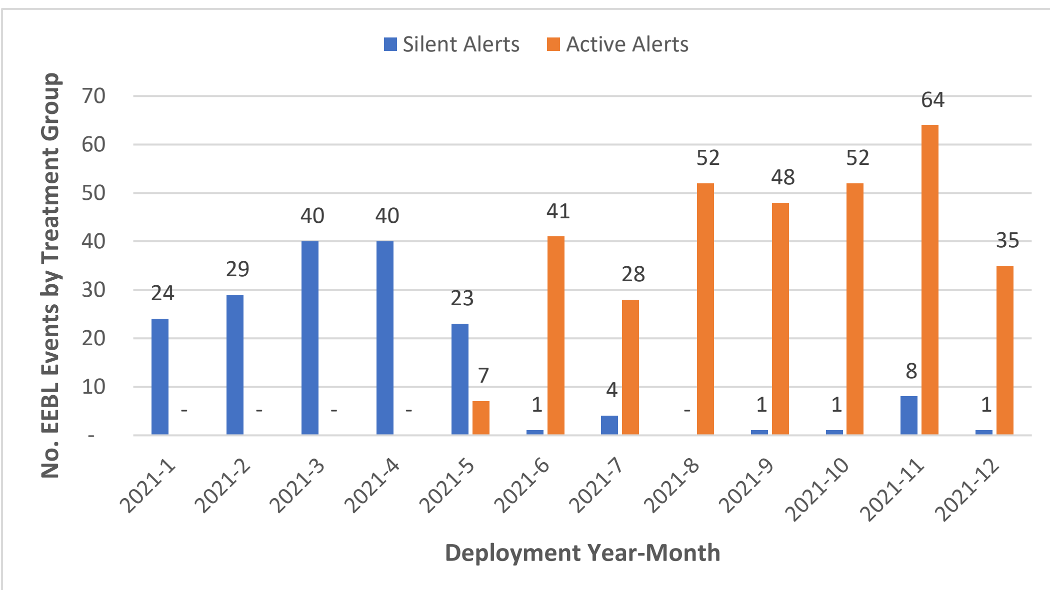


Source: U.S DOT Volpe Center

Figure 62. Distribution of All EEBL Events by Alert Status and Deployment Year and Month

5.2.1.1 EEBL Events Observed by Treatment Group

The treatment group received 499 EEBL events (91% of all EEBL events). There were 172 silent and 327 active EEBL events (34% and 66%, respectively, of treatment group EEBL events). Figure 63 illustrates the breakdown of silent and active EEBL events for the treatment group by month during the yearlong deployment.



Source: U.S DOT Volpe Center

Figure 63. Distribution of Treatment Group Events by Alert Status and Deployment Year and Month

The before period contained 156 treatment group EEBL events (31%). The after period contained 343 treatment group EEBL events (69%). Figure 64 breaks down the silent and active alerts by the before and after periods.

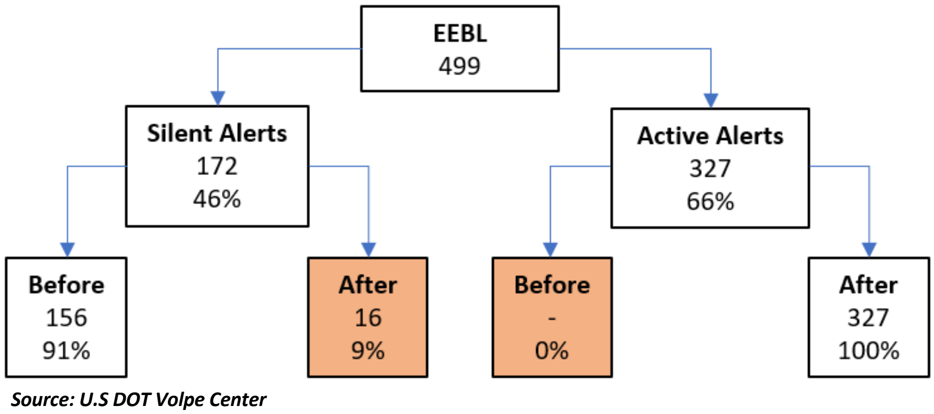
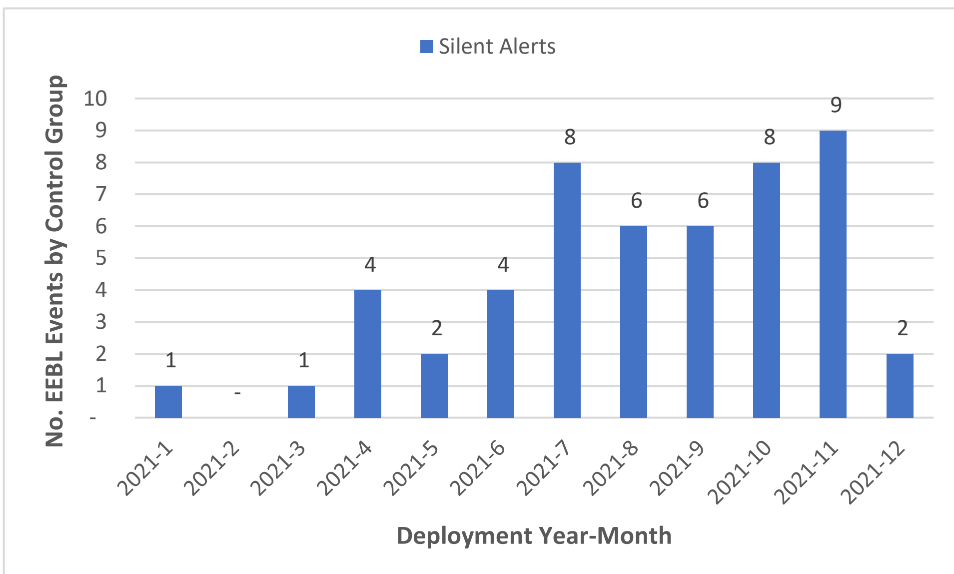


Figure 64. Breakdown of Treatment Group EEBL Events by Alert Status and Deployment Period

5.2.1.2 EEBL Events Observed by Control Group

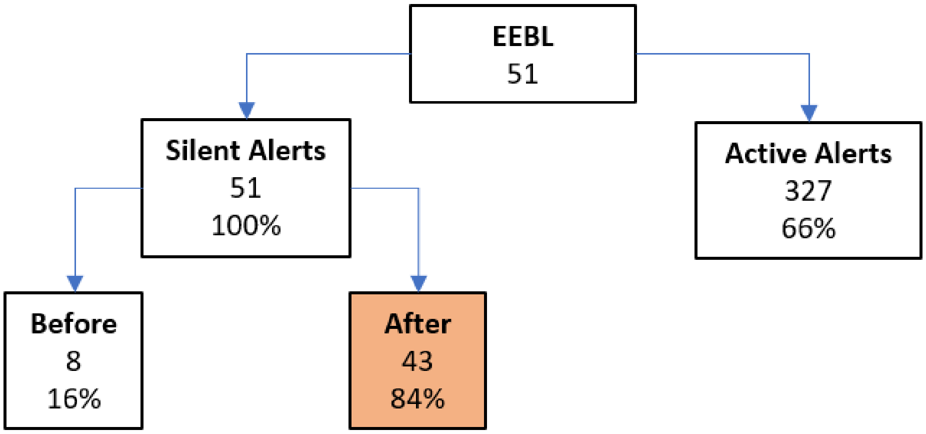
The control group experienced 51 EEBL events (9% of all EEBL events). These events comprised 51 silent EEBL events (100%) and no active EEBL events. Figure 65 illustrates the breakdown of silent and active EEBL events for the control group by month during the yearlong deployment period.



Source: U.S DOT Volpe Center

Figure 65. Distribution of Control Group EEBL Events by Alert Status and Deployment Year and Month

The before period contained eight control group EEBL events (16%). The after period contained 43 control group EEBL events (84%). Figure 66 breaks down the number of silent and active alerts by the before and after periods.



Source: U.S DOT Volpe Center

Figure 66. Breakdown of Control Group EEBL Events by Alert Status and Deployment Period

5.2.2 Data Filtering of EEBL Events

The Volpe team removed EEBL events from the analysis due to data and alert validity issues.

5.2.2.1 EEBL Events with Data Issues

The Volpe team removed some EEBL events from the analysis due to data collection and processing issues, including :

1. The pre-warning or post-warning recording times were insufficient.
2. The trajectory of the HV or RV was discontinuous or unreasonable.
3. The HV or RV did not have range or relative position data (i.e., the obfuscated GPS data was missing).
4. The HV or RV speed was unrealistic or erroneous (i.e., greater than 55 mph).
5. The HV or RV x-y coordinates indicated it was stationary while its speed was non-zero.

Table 41 indicates the number of discarded EEBL events for each filtering condition listed above. Filtering was applied independently of the control and treatment groups, silent and active alerts, and before and after periods. The filtering process removed 257 EEBL events (47%) of all EEBL events. The Volpe team deemed the remaining 293 EEBL events to be acceptable for further analysis.

Table 59. Filtering Results of EEBL Events with Data Issues

Data Quality	Count	Percentage
Insufficient pre- or post-warning times	3	0.5%
Unreasonable Vehicle Trajectory	3	0.5%
Unavailable range or relative position data	241	43.8%
Speed > 55 mph	9	1.6%
Incorrect X-Y Conversion	1	0.2%
Good Data	293	53.3%
Total	550	100.0%

5.2.2.2 EEBL Events with Invalid Alerts

The Volpe team removed EEBL events from the analysis that were deemed to have experienced invalid alerts due to limitations in application capability, including:

1. There was a substantial elevation difference between the HV and RV (based on a minimum vertical clearance for a bridge over a roadway, at least 32.8 feet (10 meters)).
2. The RV was not in the forward path (i.e., same or adjacent lane ahead) of the HV.
3. The HV speed at alert onset was below 1.1 m/s.
4. The magnitude of the RV deceleration is less than 3.5 m/s^2.

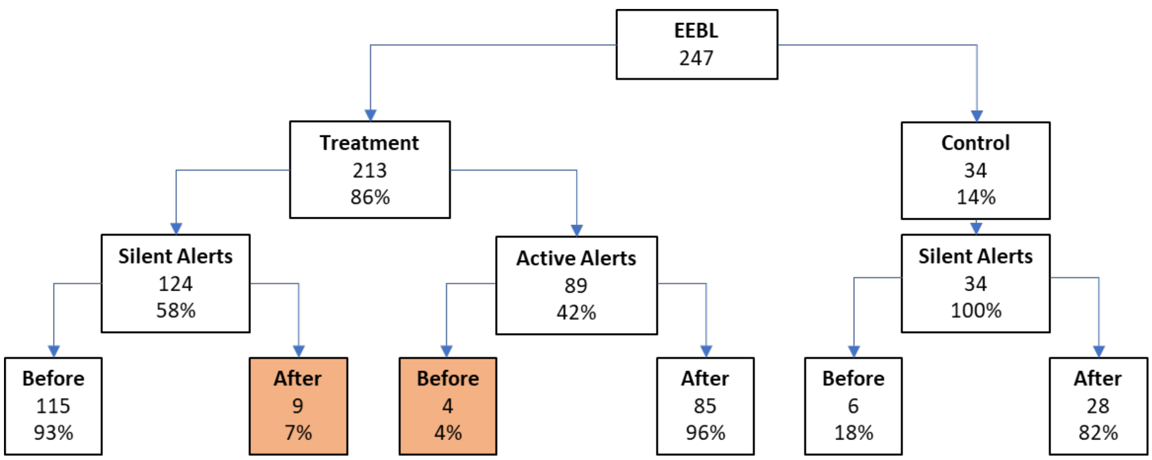
Table 42 indicates the number of discarded EEBL events for each filtering condition listed above. Filtering was applied independently of the control and treatment groups, silent and active alerts, and before and after periods. The filtering process removed 46 invalid EEBL events (16% of the acceptable EEBL events). The Volpe team will assess the safety impact of the EEBL application based on the remaining 247 EEBL events which were deemed to be valid.

Table 60. Filtering Results of EEBL Events with Invalid Alerts

Alert Validity	Count	Percentage
Elevation discrepancy	15	5.1%
RV not in-path or adjacent Lane of HV	30	10.2%
RV deceleration less than 3.5 m/s^2	1	0.3%
Valid	247	84.3%
Total	293	100.0%

5.2.2.3 EEBL Events with Valid Alerts

The filtering of the data yielded 247 EEBL events with valid alerts (45% of all observed EEBL events). Figure 67 illustrates the breakdown of these events by treatment and control groups, silent and active alerts, and before and after periods.



Source: U.S DOT Volpe Center

Figure 67. Breakdown of Valid EEBL Events by Experimental Group, Alert Status, and Deployment Period

The treatment group erroneously received nine silent alerts in the after period and four active alerts in the before period (designated by red cells in Figure 67). These events represent 13 alerts or 6% of all treatment group EEBL events with valid alerts. These alerts, while valid, would generally be excluded from the safety impact analysis. The safety impact analysis normally compares the performance of the treatment group in the before period (with appropriately silent alerts) to the after period (with appropriately active alerts).

5.2.3 Valid EEBL Data Analysis

In order to assess the safety impact of EEBL on the treatment group, the analysis compares the performance of such a group in the before period with all silent alerts to the after period with all active alerts. From Figure 67, the treatment group had 115 silent alerts in the before period and 85 active alerts in the after period, accounting respectively for 57.5% and 42.5% of all appropriate valid EEBL alerts. The Volpe team decided to assess the safety impact of EEBL by comparing the response between all silent and all active alerts from both the treatment and control groups, based on a larger sample size.

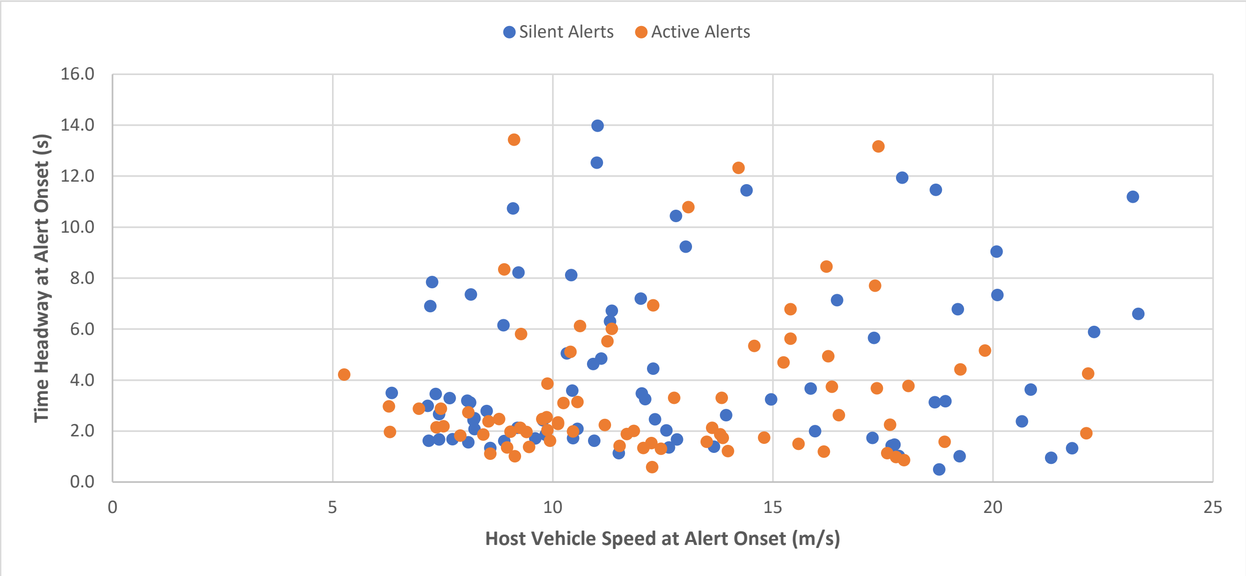
Overall, the data filtering process resulted in a total of 247 EEBL events with valid alerts. Silent and active alerts accounted for 64% (158) and 36% (89) of all EEBL events with valid alerts, respectively.

5.2.3.1 Initial Conditions of Valid EEBL Events

The Volpe team analyzed the following measures of performance for the initial conditions of EEBL events at alert onset:

1. HV speed at alert onset (m/s) ≡ $V_{HV}(0)$
2. Time headway at alert onset (s) ≡ TH(0)

Figure 69 presents a scatter plot of $V_{HV}(0)$ versus TH(0) at alert onset for valid EEBL events with silent and active alerts. Table 43 provides the descriptive statistics of $V_{HV}(0)$ and TH(0) for valid EEBL events with silent and active alerts. The 2-tailed t-tests, not assuming equal variances, show no statistically-significant difference in $V_{HV}(0)$ between silent and active alerts in valid EEBL events. On the other hand, there is a statistically-significant difference in TH(0) at the 94% confidence level between silent and active alerts in valid EEBL events. The HV speed would more likely impact vehicle/driver response to EEBL alerts than the time headway since there might be other vehicles in between the RV and HV.



Source: U.S DOT Volpe Center

Figure 68. Scatter Plot of $V_{HV}(0)$ vs TH(0) for LCW Events with Silent and Active Alerts

Table 61. Descriptive Statistics and Paired t-Test Results of $V_{HV}(0)$ (m/s) and TH(0) (s) for EEBL Events with Silent and Active Alerts

Parameter	Alert Status	Count	Mean	StdDev	Minimum	Median	Maximum	P(T<=t)
$V_{HV}(0)$	Silent	158	12.38	4.27	5.98	11.09	23.30	
	Active	89	12.36	3.98	5.26	11.58	22.16	0.96
TH(0)	Silent	158	5.30	5.48	0.50	3.13	31.23	
	Active	89	4.08	4.51	0.59	2.48	28.82	0.06

5.2.3.2 Vehicle/Driver Response to Valid EEBL Events

The measures of performance for vehicle/driver response after EEBL alert onset included the following measures:

1. Count of events that resulted in an HV brake response (logical yes or no)
2. Count of events that resulted in HV speed reduction by 2.2 m/s (5 mph) or more (logical yes or no)
3. HV brake reaction time (s) ≡ BRT
4. HV average deceleration from brake application until HV minimum speed (m/s^2) ≡ A_{HV}

Table 44 presents the results of the brake application and speed reduction responses to EEBL events with silent and active alerts, along with the results of the odds ratio test. Brake application was observed in 72% of EEBL events with active alerts and in 61% of such events with silent alerts. Similarly, EEBL events with active alerts experienced higher speed reduction rate than with silent alerts, 80% versus 72%. However, the difference is only statistically significant in the brake application rate at 92% confidence level.

Table 62. Statistics of HV Brake Application and Speed Reduction in Response to EEBL Events with Silent and Active Alerts

Parameter	Alert Status	No	Yes	Odds Ratio	Lower 95% CI	Upper 95% C	P-Value
Brake Application	Silent	62	96				
	Active	25	64	1.65	0.94	2.90	0.08
Speed Reduction	Silent	44	114				
	Active	18	71	1.52	0.82	2.84	0.19

Table 45 presents the statistical results of brake reaction time and average deceleration of the HV in response to EEBL silent and active alerts, together with the paired t-test results. Active alerts in EEBL events elicited faster brake reaction time than silent alerts of 1.0 s versus 1.4 s, which is statistically significant at 97% confidence level. In contrast, silent alerts in EEBL events produced larger average deceleration than active alerts of 2.24 m/s^2 versus 2.07 m/s^2, which is only statistically significant at 92% confidence level. Having faster reaction time and smaller braking level is desirable from a safety perspective.

Table 63. Statistics of HV Brake Reaction Time and Average Deceleration in Response to EEBL Events with Silent and Active Alerts

Parameter	**Alert Status**	**Count**	**Mean**	**StdDev**	**Minimum**	**Median**	**Maximum**	**P(T<=t)**
Brake Reaction Time (s)	Silent	84	1.39	1.08	0.10	1.00	4.90	0.03
	Active	54	1.02	0.90	0.10	0.70	4.10	
Average Deceleration (m/s^2)	Silent	96	(2.24)	0.63	(4.14)	(2.21)	(0.95)	0.08
	Active	64	(2.07)	0.59	(3.69)	(2.06)	(0.74)	

5.2.4 EEBL Safety Effectiveness

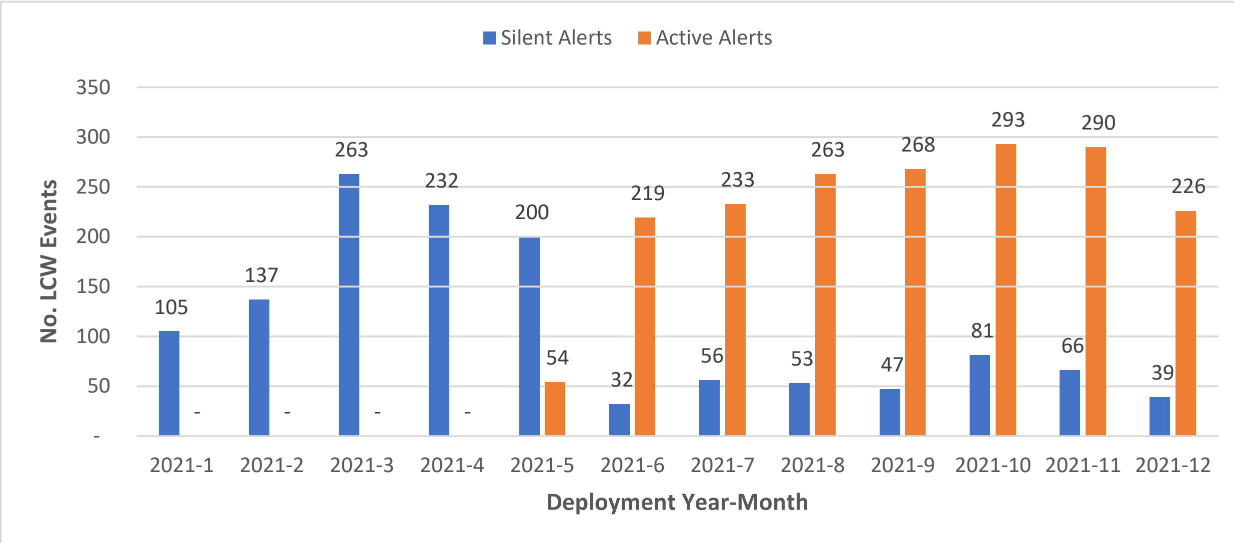
The EEBL application was very effective in reducing:

1. Rate of non-brake application by 28% at the 92% confidence level, from 39% by silent alerts down to 28% by active alerts.
2. Brake reaction time by 26% at the 97% confidence level, from 1.39 s by silent alerts down to 1.02 s by active alerts.
3. Average deceleration level by 8% at the 92% confidence level, from 2.24 m/s^2 by silent alerts down to 2.07 m/s^2 by active alerts.

5.3 Lane Change Warning

5.3.1 Observed LCW Events

The SDC contained 3,157 LCW events from the NYC CVP deployment. These events comprised 1,311 silent LCW events (42%) and 1,846 active LCW events (58%). Figure 69 illustrates the breakdown of silent and active LCW events by month during the yearlong deployment. In the before period, there were 937 LCW events (30%). In the after period, there were 2,220 LCW events (70%).

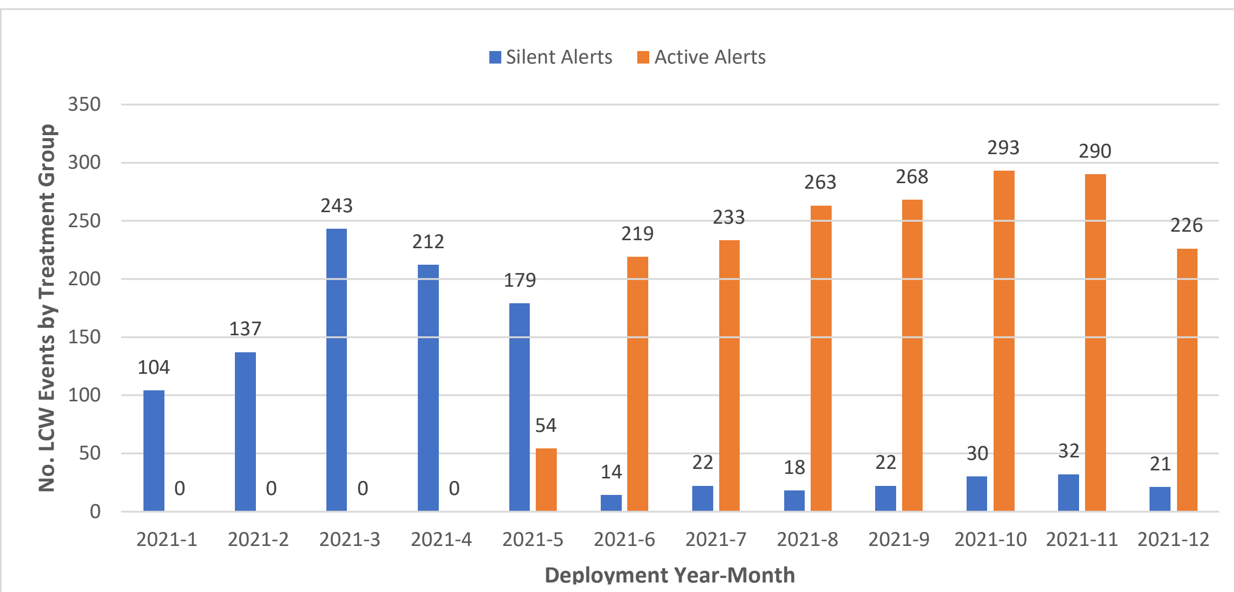


Source: U.S DOT Volpe Center

Figure 69. Distribution of All LCW Events by Alert Status and Deployment Year and Month

5.3.1.1 LCW Events Observed by Treatment Group

The treatment group received 2,880 LCW events (91% of all LCW events). There were 1,034 silent and 1,846 active LCW events (36% and 64%, respectively, of treatment group LCW events). Figure 70 illustrates the breakdown of silent and active LCW events for the treatment group by month during the yearlong deployment.



Source: U.S DOT Volpe Center

Figure 70. Distribution of Treatment Group LCW Events by Alert Status and Deployment Year and Month

The before period contained 875 treatment group LCW events (30%). The after period contained 2,005 treatment group LCW events (70%). Figure 71 breaks down the silent and active alerts by the before and after periods.

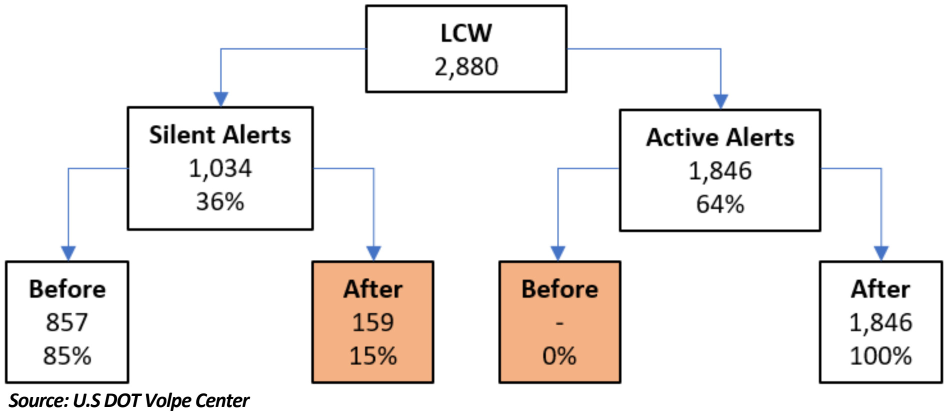
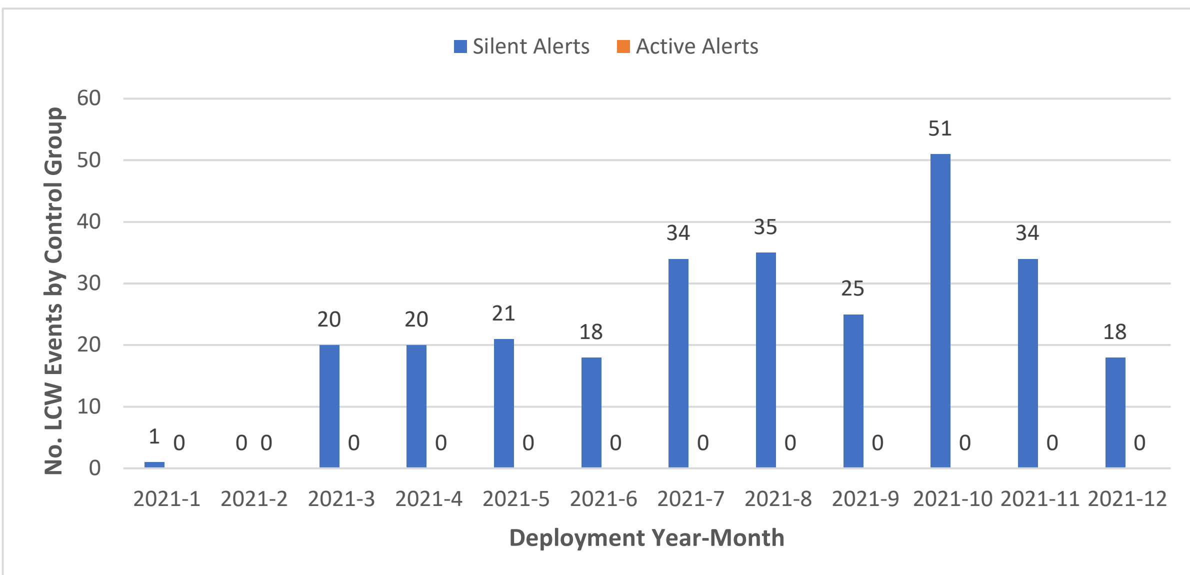


Figure 71. Breakdown of Treatment Group LCW Events by Alert Status and Deployment Period

5.3.1.2 LCW Events Observed by Control Group

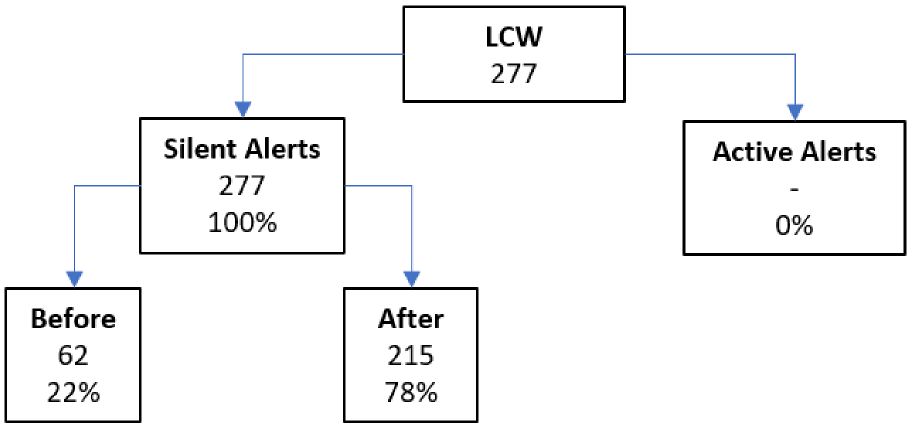
The control group experienced 277 LCW events (9% of all LCW events). These events comprised 277 silent LCW events (100%) and no active LCW events. Figure 72 illustrates the breakdown of silent and active LCW events for the control group by month during the yearlong deployment period.



Source: U.S DOT Volpe Center

Figure 72. Distribution of Control Group LCW Events by Alert Status and Deployment Year and Month

The before period contained 62 control group LCW events (22%). The after period contained 215 control group LCW events (78%). Figure 73 breaks down the number of silent and active alerts by the before and after periods.



Source: U.S DOT Volpe Center

Figure 73. Breakdown of Control Group LCW Events by Alert Status and Deployment Period

5.3.2 Data Filtering of LCW Events

The Volpe team removed LCW events from the analysis due to data and alert validity issues.

5.3.2.1 LCW Events with Data Issues

The Volpe team removed some LCW events from the analysis due to data collection and processing issues, including:

1. The pre-warning or post-warning recording times were insufficient.
2. The trajectory of the HV or RV was discontinuous or unreasonable.
3. The HV or RV did not have range or relative position data (i.e., the obfuscated GPS data was missing).
4. The HV or RV speed was unrealistic or erroneous (i.e., greater than 55 mph).
5. The HV or RV x-y coordinates indicated it was stationary while its speed was non-zero.

Table 43 indicates the number of discarded LCW events for each filtering condition listed above. Filtering was applied independently of the control and treatment groups, silent and active alerts, and before and after periods. The filtering process removed 1,287 LCW events (41%) of all LCW events. The Volpe team deemed the remaining 1,870 LCW events to be acceptable for further analysis.

Table 64. Filtering Results of LCW Events with Data Issues

Data Quality	Count	Percentage
Insufficient pre- or post-warning times	22	0.7%
Unreasonable Vehicle Trajectory	29	0.9%
Unavailable range data	800	25.3%
Speed > 55 mph	405	12.8%
Incorrect X-Y Conversion	31	1.0%
Good Data	1,870	59.2%
Total	3,157	100.0%

5.3.2.2 LCW Events with Invalid Alerts

The Volpe team removed LCW events from the analysis that were deemed to have experienced invalid alerts due to limitations in application capability, including:

1. There was a substantial elevation difference between the HV and RV (based on a minimum vertical clearance for a bridge over a roadway, at least 32.8 feet (10 meters)).
2. The HV speed at alert onset was below 1.1 m/s.
3. The RV was not in adjacent lanes of the HV at alert onset.
4. The RV was in adjacent lanes behind the HV but separating or the time-to-collision was greater than 5.5 seconds.

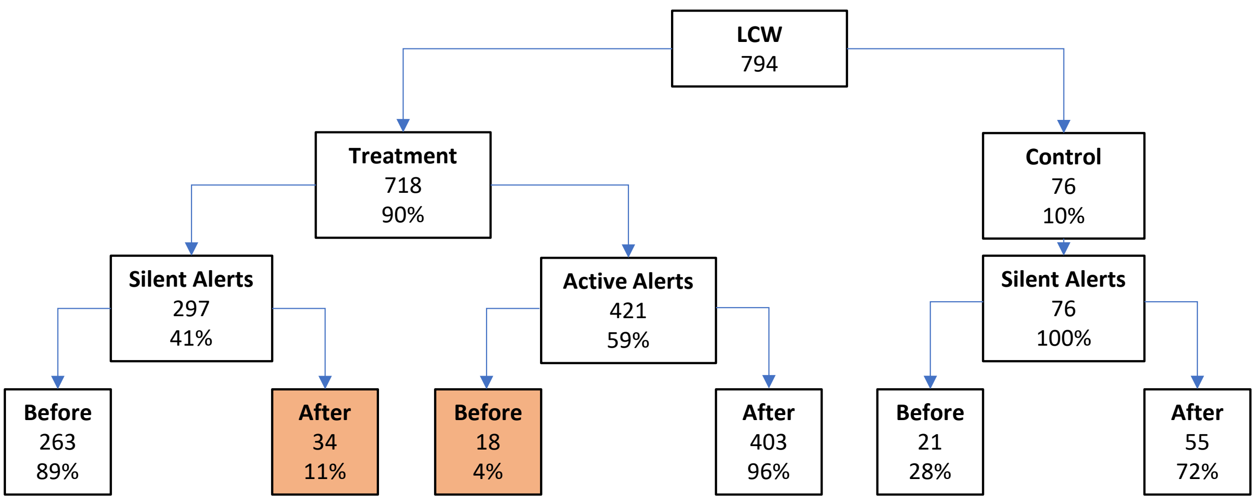
Table 44 indicates the number of discarded LCW events for each filtering condition listed above. Filtering was applied independently of the control and treatment groups, silent and active alerts, and before and after periods. The filtering process removed 1,076 invalid LCW events (58% of the acceptable LCW events). The Volpe team will assess the safety impact of the LCW application based on the remaining 794 LCW events which were deemed to be valid.

Table 65. Filtering Results of LCW Events with Invalid Alerts

Alert Validity	Count	Percentage
Elevation discrepancy	115	6.1%
HV speed < 1.1 m/s	1	0.1%
RV Not in Adjacent Lanes	728	38.9%
RV in Adjacent Lanes behind HV but Separating OR TTC > 5.5 s	232	12.4%
Valid	794	42.5%
Total	1,870	100.0%

5.3.2.3 LCW Events with Valid Alerts

The filtering of the data yielded 794 LCW events with valid alerts (25% of all observed LCW events). Figure 74 illustrates the breakdown of these events by treatment and control groups, silent and active alerts, and before and after periods.



Source: U.S DOT Volpe Center

Figure 74. Breakdown of Valid LCW Events by Experimental Group, Alert Status, and Deployment Period

The treatment group erroneously received 34 silent alerts in the after period and 18 active alerts in the before period (designated by red cells in Figure 74). These events represent 52 alerts or 7% of all treatment group LCW events with valid alerts. These alerts, while valid, would generally be excluded from the safety impact analysis. The safety impact analysis normally compares the performance of the treatment group in the before period (with appropriately silent alerts) to the after period (with appropriately active alerts).

5.3.3 Valid LCW Data Analysis

In order to assess the safety impact of LCW on the treatment group, the analysis compares the performance of such a group in the before period with all silent alerts to the after period with all active alerts. From Figure 74, the treatment group had 263 silent alerts in the before period and 403 active alerts in the after period, accounting respectively for 39% and 61% of all proper valid LCW alerts. Thus, the proportion of silent alerts is much smaller than the proportion of active alerts to efficiently perform statistical comparison of the treatment group performance between the before and after periods. Consequently, the Volpe team decided to assess the safety impact of LCW by comparing the response between all silent and all active alerts from both the treatment and control groups.

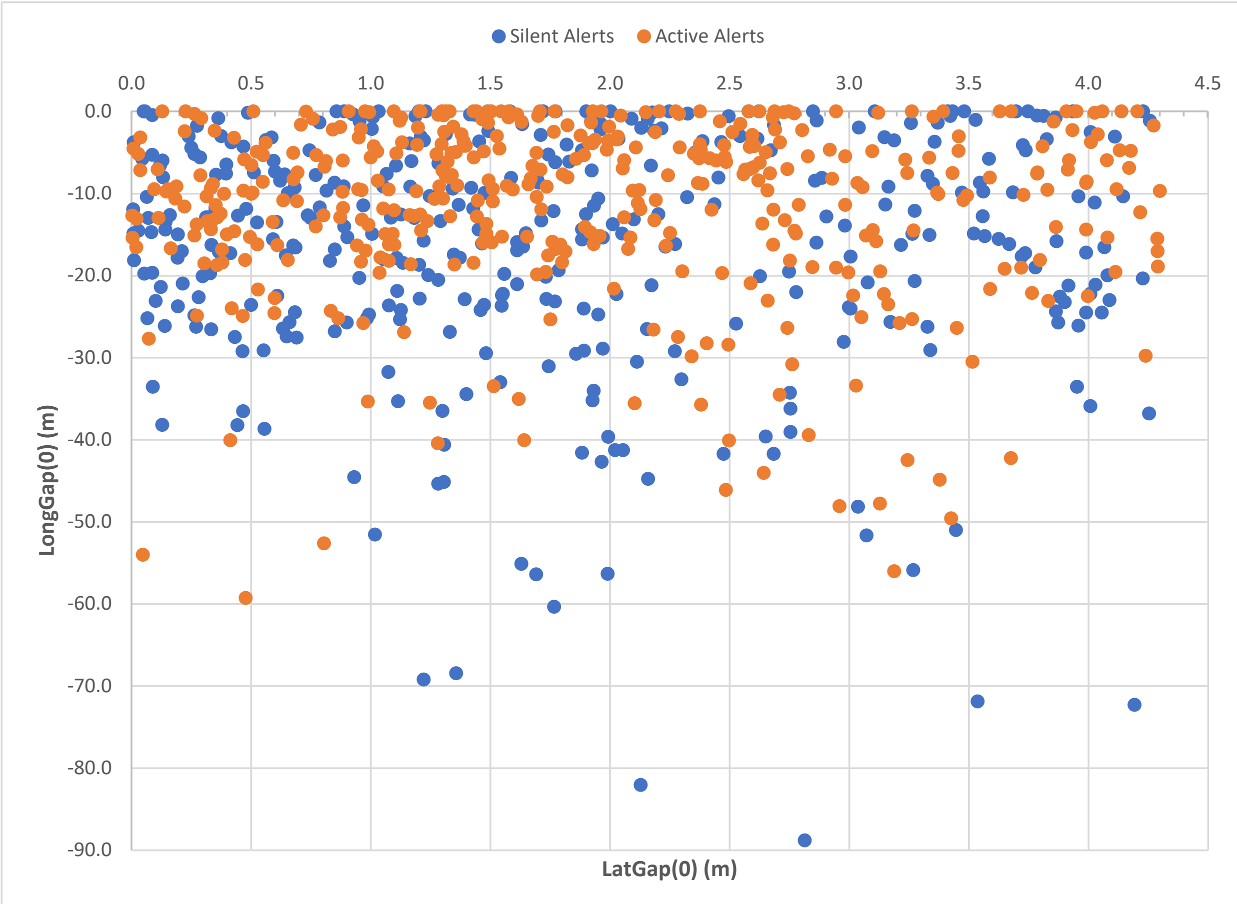
Overall, the data filtering process resulted in a total of 794 LCW events with valid alerts for further analysis. Silent and active alerts accounted for 47% (373) and 53% (421) of all LCW events with valid alerts, respectively.

5.3.3.1 Initial Conditions of Valid LCW Events

The Volpe team analyzed the following measures of performance for the initial conditions of this event:

1. Lateral gap between the sides of the HV and RV at alert onset (m) ≡ LatGap(0). The value of this parameter is greater than zero when there is no lateral overalp, and less than or equal to zero when otherwise.
2. Time to longitudinal overlap between the HV and RV at alert onset (s) ≡ TTO(0) = absolute value of LongGap(0) / Rdot(0), where:
    a. LongGap(0) is the longitudinal gap between the front of one vehicle to the rear of another vehicle at alert onset (m). The value of this parameter is greater than zero when the RV is ahead of the HV, less than zero when the RV is behind the HV, and zero when there is any longitudinal overalp.
    b. Rdot(0) is the range rate (m/s) = $V_{RV}(0) – V_{HV}(0)$

Figure 75 presents a scatter plot of LatGap(0) versus LongGap(0) at alert onset for valid LCW events with silent and active alerts. Table 45 provides the descriptive statistics of LatGap(0) and TTO(0) for valid LCW events with silent and active alerts. It should be noted that the event counts for TTO(0) are less than the counts for LatGap(0) due to the exclusion of events where the HV was separating from the RV (i.e., HV traveling at a higher speed than the RV). The 2-tailed t-tests, not assuming equal variances, show no statistically-significant differences in LatGap(0) and TTO(0) between silent and active alerts in valid LCW events. Thus, the valid LCW events with silent or active alerts experienced similar initial conditions at alert onset.



Source: U.S DOT Volpe Center

Figure 75. Scatter Plot of LatGap(0) vs LongGap(0) for LCW Events with Silent and Active Alerts

Table 66. Descriptive Statistics and Paired t-Test Results of LatGap(0) (m) and TTO(0) (s) for LCW Events with Silent and Active Alerts

Parameter	Alert Status	Count	Mean	StdDev	Minimum	Median	Maximum	P(T<=t)
LatGap(0) (m)	Silent	373	1.80	1.21	0.01	1.63	4.26	
	Active	421	1.90	1.15	0.00	1.74	4.30	0.25
TTO(0) (s)	Silent	362	3.78	2.53	-	4.43	32.21	
	Active	391	3.69	4.64	-	3.89	80.56	0.74

5.3.3.2 *Vehicle/Driver Response to Valid LCW Events*

The measures of performance for vehicle/driver response after LCW alert onset included the following logical (yes or no) measures:

1. Count of events that resulted in a lane change by either the HV or RV.
2. Count of unsafe events as a result of a lane change by either the HV or RV.

The Volpe team developed and applied the following logic to quantify these two measures of performance:

If ***LatGap***(t > ***0*** > 0, then "no' lane change {safe outcome} where t = 0 is LCW alert onset time.
Else {lane change occurred}
If ***LongGap***(***tLEZ***) > 0, then RV is ahead of HV where ***tLEZ*** = time when LatGap becomes Less than or equal to zero after LCW alert onset.
If $V_{RV} \geq V_{HV}$, then RV and HV are following or separating {safe outcome}
Elseif TTC ≥ 3 s, then HV is closing in on RV with long TTC {safe outcome}
Else HV is closing in on RV with short TTC {unsafe outcome}
Else (HV remains ahead of RV}
If $V_{HV} \geq V_{RV}$, then RV and HV are following or separating {safe outcome}
Elseif TTC ≥ 3 s, then RV is closing in on HV with long TTC {safe outcome}
Else RV is closing in on HV with short TTC {unsafe outcome}

Table 46 provides the results of applying the above logic to valid LCW events. LCW events with silent alerts resulted in 190 lane changes out of 360 events (53%) and LCW events with active alerts resulted in 187 lane changes out of 404 events (46%). Moreover, 28 LCW events with silent alerts out of 360 events (8%) experienced an unsafe outcome whereas 17 LCW events with active alerts out of 404 events (4%) experienced an unsafe outcome.

Table 67. Outcome of Vehicle/Driver Response to Valid LCW Events by Alert Status

Alert Status	Lane Change	Safe OutCome	Relative Position between RV and HV	Event Count	Rate
Silent	No	Safe	No Lane change	170	21%
	Yes		RV front, separating	35	4%
			HV front, separating	69	9%
			Closing, TTC ≥ 3 s	58	7%
		Unsafe	Closing, TTC < 3 s	28	4%
	Unknown	Unknown	Overlap	13	2%
Active	No	Safe	No Lane change	217	27%
	Yes		RV front, separating	39	5%
			HV front, separating	83	10%
			Closing, TTC ≥ 3 s	48	6%
		Unsafe	Closing, TTC < 3 s	17	2%
	Unknown	Unknown	Overlap	17	2%
			TOTAL	**794**	**100%**

Table 47 shows the results of the odds ratio tests for the lane change and safe outcome measures, which indicate statistically-signifcant differences between silent and active alerts in valid LCW events. Clearly, active alerts yielded slightly less lane changes and much less unsafe outcomes than silent alerts.

Table 68. Odds Ratio Test Results of Vehicle/Driver Response to Valid LCW Events

Descriptor	Lane Change	Safe Outcome
Odds ratio	1.30	1.92
Lower 95% Confidence Interval	0.98	1.03
Upper 95% Confidence Interval	1.72	3.57
P-value	0.07	0.04

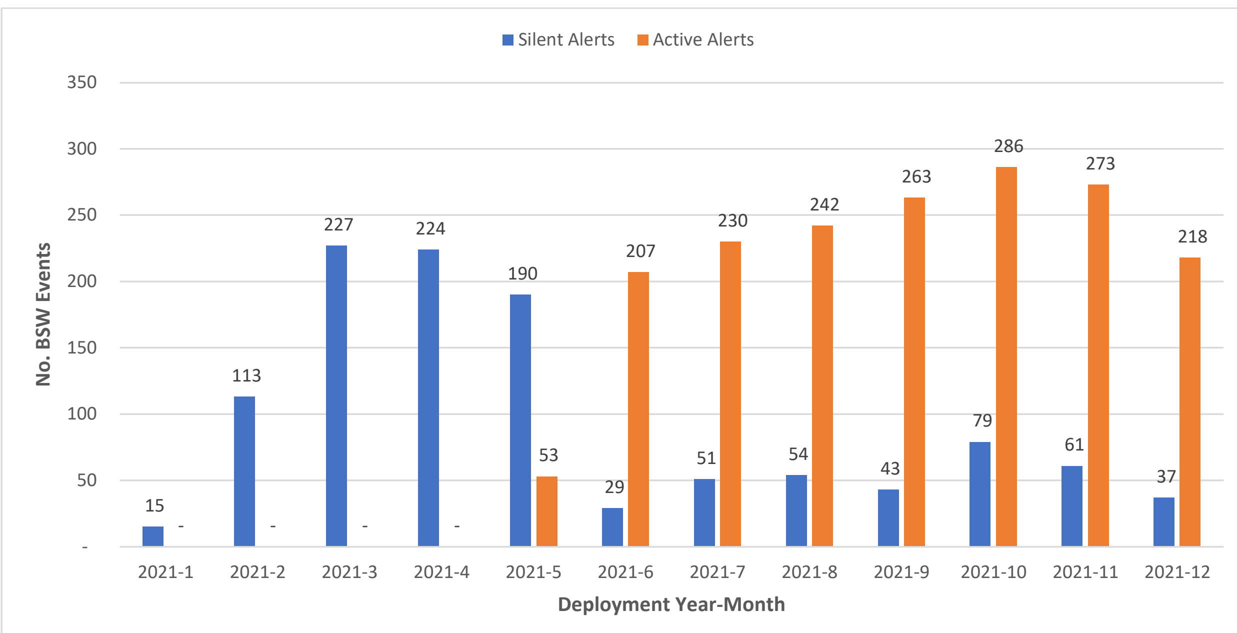
5.3.4 LCW Safety Effectiveness

The LCW application was very effective in reducing the rate of unsafe lane changes by 46% at the 96% confidence level. However, this application was effective but at a lesser degree in reducing the rate of lane change maneuvers by 12% at the 93% confidence level.

5.4 Blind Spot Warning

5.4.1 Observed BSW Events

The SDC contained 2,895 BSW events from the NYC CVP deployment. These events comprised 1,123 silent BSW events (39%) and 1,772 active BSW events (61%). Figure 77 illustrates the breakdown of silent and active BSW events by month during the yearlong deployment. In the before period, there were 769 BSW events (27%). In the after period, there were 2,126 BSW events (73%).

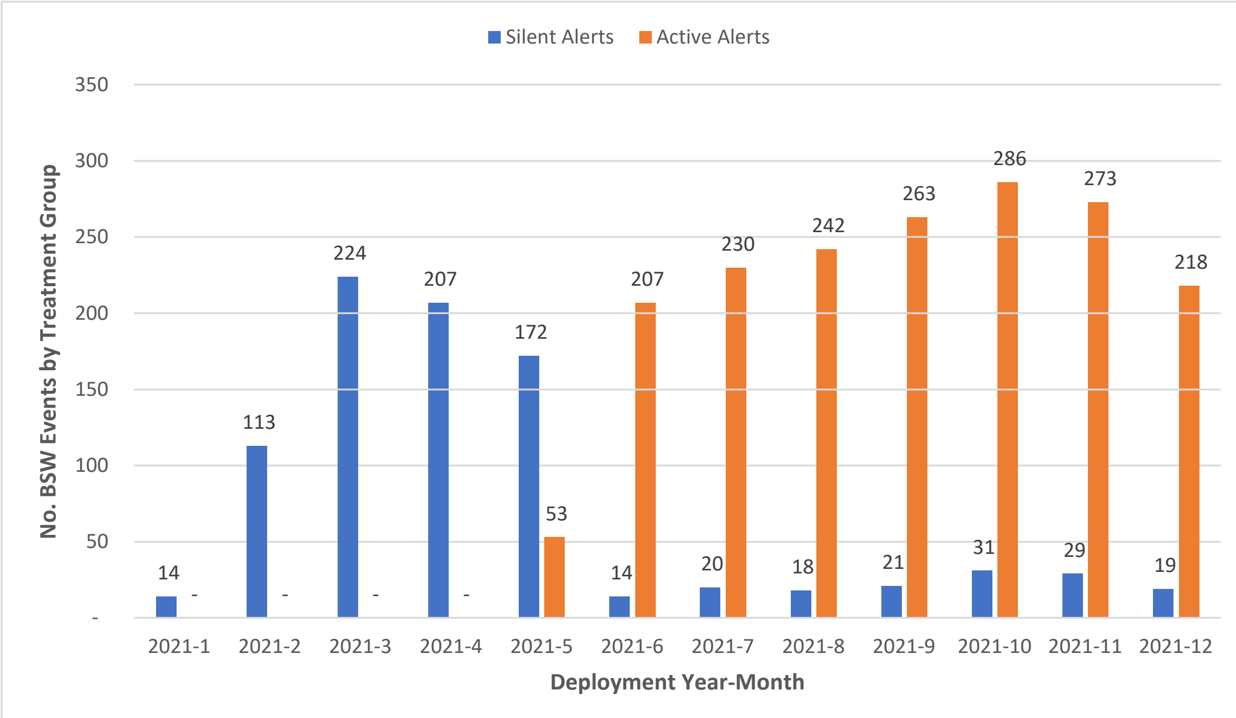


Source: U.S DOT Volpe Center

Figure 76. Distribution of All BSW Events by Alert Status and Deployment Year and Month

5.4.1.1 BSW Events Observed by Treatment Group

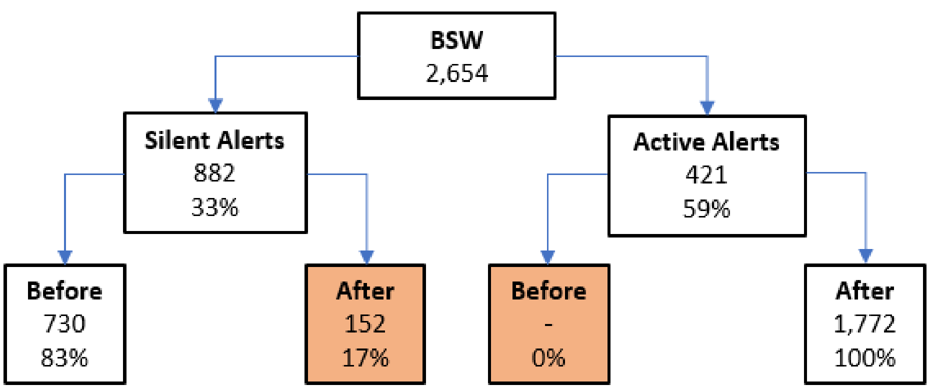
The treatment group received 2,654 BSW events (92% of all BSW events). There were 882 silent and 1,772 active BSW events (33% and 67%, respectively, of treatment group BSW events). Figure 77 illustrates the breakdown of silent and active BSW events for the treatment group by month during the yearlong deployment.



Source: U.S DOT Volpe Center

Figure 77. Distribution of Treatment Group BSW Events by Alert Status and Deployment Year and Month

The before period contained 730 treatment group BSW events (28%). The after period contained 1,924 treatment group BSW events (72%). Figure 78 breaks down the number of silent and active alerts by the before and after periods.

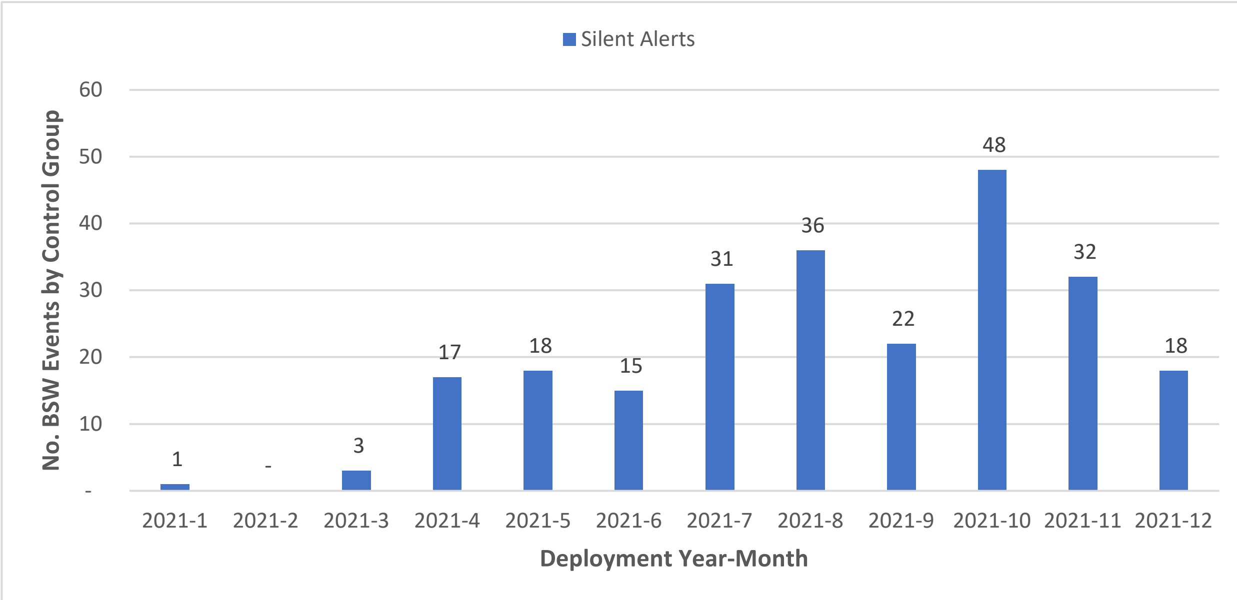


Source: U.S DOT Volpe Center

Figure 78. Breakdown of Treatment Group BSW Events by Alert Status and Deployment Period

5.4.1.2 BSW Events Observed by Control Group

The control group experienced 241 BSW events (8% of all BSW events). These events comprised 241 silent BSW events (100%) and no active BSW events. Figure 79 illustrates the breakdown of silent and active BSW events for the control group by month during the yearlong deployment period.



Source: U.S DOT Volpe Center

Figure 79. Distribution of Control Group BSW Events by Alert Status and Deployment Year and Month

The before period contained 39 control group BSW events (16%). The after period contained 202 control group BSW events (84%). Figure 80 breaks down the number of silent and active alerts by the before and after periods.

Source: U.S DOT Volpe Center

Figure 80. Breakdown of Control Group BSW Events by Alert Status and Deployment Period

5.4.2 Data Filtering of BSW Events

The Volpe team removed BSW events from the analysis due to data and alert validity issues.

5.4.2.1 BSW Events with Data Issues

The Volpe team removed some BSW events from the analysis due to data collection and processing issues, including:

1. The pre-warning or post-warning recording times were insufficient.
2. The trajectory of the HV or RV was discontinuous or unreasonable.

3. The HV or RV did not have range or relative position data (i.e., the obfuscated GPS data was missing).
4. The HV or RV speed was unrealistic or erroneous (i.e., greater than 55 mph).
5. The HV or RV x-y coordinates indicated it was stationary while its speed was non-zero.

Table 48 indicates the number of discarded BSW events for each filtering condition listed above. Filtering was applied independently of the control and treatment groups, silent and active alerts, and before and after periods. The filtering process removed 1,117 BSW events (39%) of all BSW events. The Volpe team deemed the remaining 1,778 BSW events to be acceptable for further analysis.

Table 69. Filtering Results of BSW Events with Data Issues

Data Quality	Count	Percentage
Insufficient pre- or post-warning times	18	0.6%
Unreasonable Vehicle Trajectory	22	0.8%
Unavailable range data	682	23.6%
Speed > 55 mph	370	12.8%
Incorrect X-Y Conversion	25	0.9%
Good Data	1,778	61.4%
Total	2,895	100.0%

5.4.2.2 BSW Events with Invalid Alerts

The Volpe team removed BSW events from the analysis that were deemed to have experienced invalid alerts due to limitations in application capability, including:

1. There was a substantial elevation difference between the HV and RV (based on a minimum vertical clearance for a bridge over a roadway, at least 32.8 feet (10 meters)).
2. The HV speed at alert onset was below 1.1 m/s.
3. The RV was not in the blind spot of the HV at alert onset.

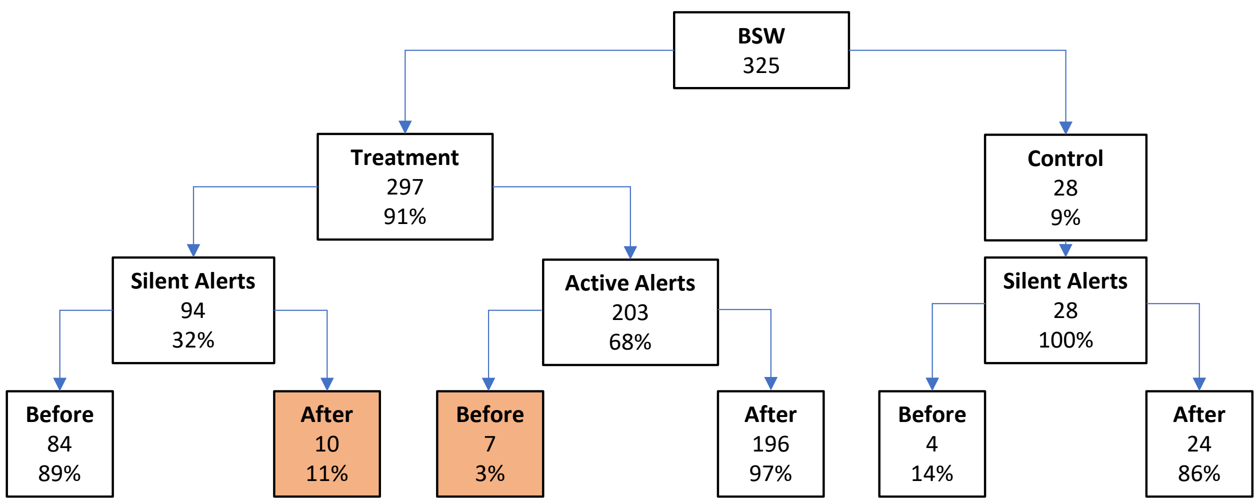
Table 49 indicates the number of discarded BSW events for each filtering condition listed above. Filtering was applied independently of the control and treatment groups, silent and active alerts, and before and after periods. The filtering process removed 1,453 invalid BSW events (82% of the acceptable BSW events). The Volpe team will assess the safety impact of the BSW application based on the remaining 325 BSW events which were deemed to be valid.

Table 70. Filtering Results of BSW Events with Invalid Alerts

Alert Validity	Count	Percentage
Elevation discrepancy	113	6.4%
HV speed < 1.1 m/s	-	0.0%
RV not in blind spot of HV	1,340	75.4%
Valid	325	18.3%
Total	1,778	100.0%

5.4.2.3 *BSW Events with Valid Alerts*

The filtering of the data yielded 325 BSW events with valid alerts (11% of all observed BSW events). Figure 81 illustrates the breakdown of these events by treatment and control groups, silent and active alerts, and before and after periods.



Source: U.S DOT Volpe Center

Figure 81. Breakdown of Valid BSW Events by Experimental Group, Alert Status, and Deployment Period

The treatment group erroneously received 10 silent alerts in the after period and seven active alerts in the before period (designated by red cells in Figure 82). These events represent 17 alerts or 6% of all treatment group BSW events with valid alerts. These alerts, while valid, would generally be excluded from the safety impact analysis. The safety impact analysis normally compares the performance of the treatment group in the before period (with appropriately silent alerts) to the after period (with appropriately active alerts).

5.4.3 Valid BSW Data Analysis

In order to assess the safety impact of BSW on the treatment group, the analysis compares the performance of such a group in the before period with all silent alerts to the after period with all active alerts. From Figure 81, the treatment group had 84 silent alerts in the before period and 196 active alerts in the after period, accounting respectively for 30% and 70% of all proper valid BSW alerts. Thus, the proportion of silent alerts is much smaller than the proportion of active alerts to efficiently perform statistical comparison of the treatment group performance between the before and after periods. Consequently, the Volpe team decided to assess the safety impact of BSW by comparing the response between all silent and all active alerts from both the treatment and control groups.

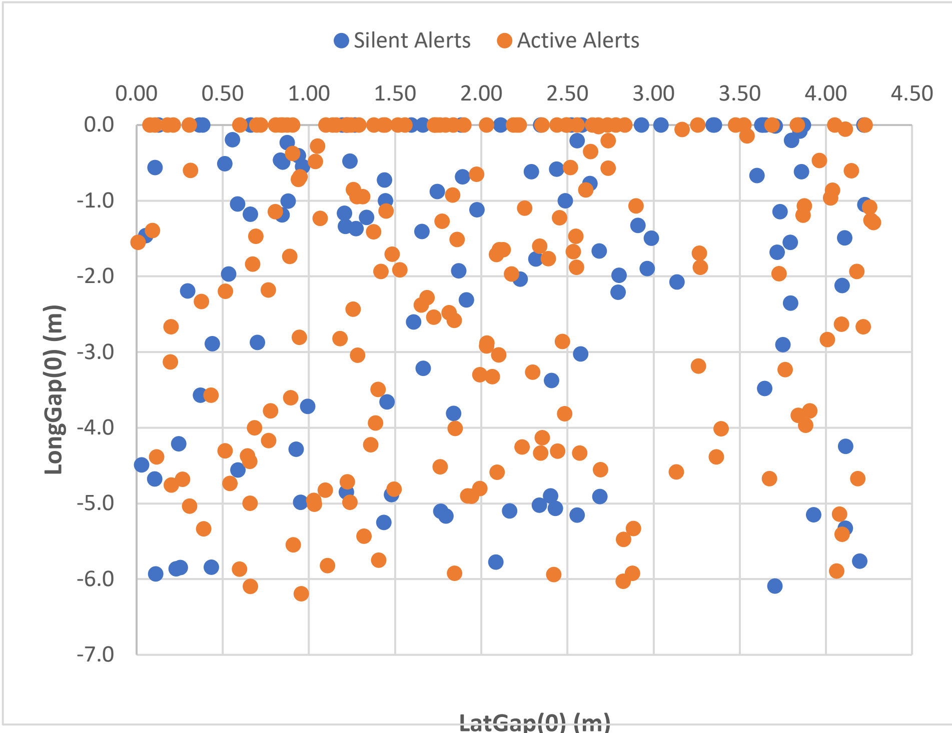
Overall, the data filtering process resulted in a total of 325 BSW events with valid alerts for further analysis. Silent and active alerts accounted for 38% (122) and 62% (203) of all BSW events with valid alerts, respectively.

5.4.3.1 Initial Conditions of Valid BSW Events

The Volpe team analyzed the following measures of performance for the initial conditions of valid BSW event:

1. LatGap(0)
2. LongGap(0)
3. TTO(0)

Figure 82 presents a scatter plot of LatGap(0) versus LongGap(0 at alert onset for valid BSW events with silent and active alerts. Table 50 provides the descriptive statistics of LatGap(0) and TTO(0) for valid BSW events with silent and active alerts. It should be noted that the event counts for TTO(0) are less than the counts for LatGap(0) due to the exclusion of events where the HV was separating from the RV (i.e., HV traveling at a higher speed than the RV). The 2-tailed t-tests, not assuming equal variances, show no statistically-significant differences in LatGap(0) and TTO(0) between silent and active alerts in valid BSW events. Thus, the valid BSW events with silent or active alerts experienced similar initial conditions at alert onset.



Source: U.S DOT Volpe Center

Figure 82. Scatter Plot of LatGap(0) vs LongGap(0) for BSW Events with Silent and Active Alerts

Table 71. Descriptive Statistics and Paired t-Test Results of LatGap(0) (m) for BSW Events with Silent and Active Alerts

Parameter	Alert Status	Count	Mean	StdDev	Minimum	Median	Maximum	P(T<=t)
LatGap(0) (m)	Silent	122	2.04	1.25	0.03	1.90	4.23	
	Active	203	1.95	1.17	0.01	1.83	4.28	0.52
TTO(0) (s)	Silent	100	1.78	3.13	-	0.56	18.78	
	Active	155	2.86	15.46	-	0.49	191.81	0.40

5.4.3.2 Vehicle/Driver Response to Valid BSW Events

The measures of performance for vehicle/driver response after BSW alert onset included the following logical (yes or no) measures:

1. Count of events that resulted in a lane change by either the HV or RV.
2. Count of unsafe events as a result of a lane change by either the HV or RV.

The Volpe team developed and applied the logic in Section 5.3.3.2 to quantify these two measures of performance. Table 51 provides the results of applying this logic to valid BSW events. BSW events with silent alerts resulted in 51 lane changes out of 113 events (45%) and BSW events with active alerts resulted in 92 lane changes out of 197 events (47%). Moreover, 5 BSW events with silent alerts out of 113 events (4%) experienced an unsafe outcome whereas 2 BSW events with active alerts out of 197 events (1%) experienced an unsafe outcome.

Table 72. Outcome of Vehicle/Driver Response to Valid BSW Events by Alert Status

Alert Status	**Lane Change**	**Safe OutCome**	**Relative Position between RV and HV**	**Event Count**	**Rate**
Silent	No	Safe	No Lane change	62	19%
	Yes	Safe	RV front, separating	15	5%
			HV front, separating	26	8%
			Closing, TTC ≥ 3 s	5	2%
		Unsafe	Closing, TTC < 3 s	5	2%
	Unknown	Unknown	Overlap	9	3%
Active	No	Safe	No Lane change	105	32%
	Yes	Safe	RV front, separating	23	7%
			HV front, separating	55	17%
			Closing, TTC ≥ 3 s	12	4%
		Unsafe	Closing, TTC < 3 s	2	1%
	Unknown	Unknown	Overlap	6	2%
			TOTAL	**325**	**100%**

Table 73 shows the results of the odds ratio tests for the lane change and safe outcome measures. BSW events with silent and active alerts had similar rates of lane change maneuvers (no statistically-significant difference), but statistically-significant difference in unsafe outcome at 93% confidence level (very small counts of unsafe outcome by both groups).

Table 73. Odds Ratio Test Results of Vehicle/Driver Response to Valid BSW Events

Descriptor	**Lane Change**	**Safe Outcome**
Odds ratio	0.94	4.51
Lower 95% Confidence Interval	0.59	0.86
Upper 95% Confidence Interval	1.49	23.66
P-value	0.79	0.07

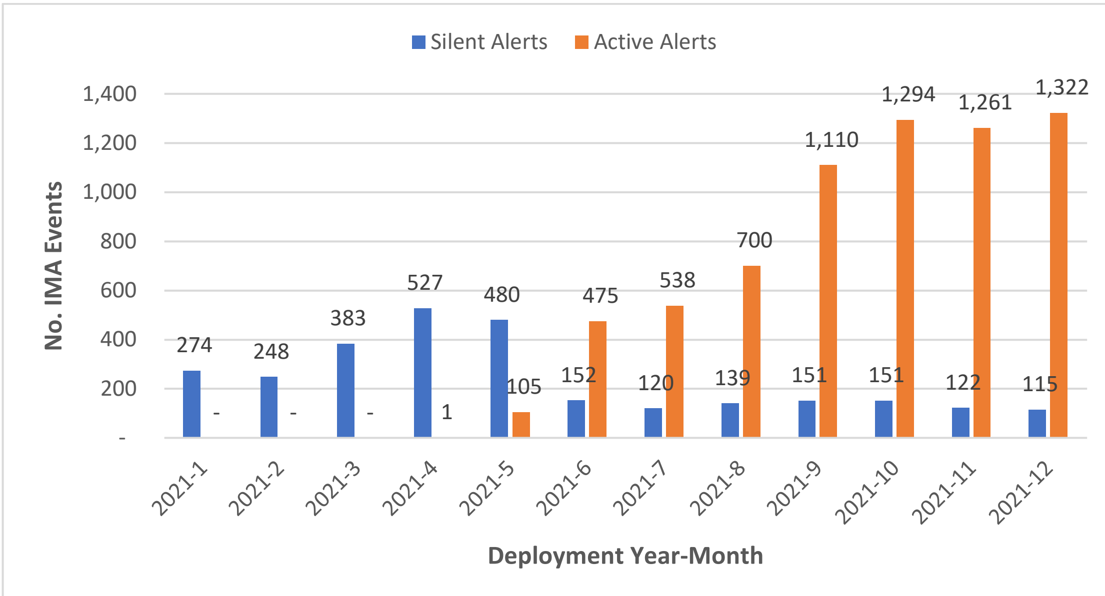
5.4.4 BSW Safety Effectiveness

Based on available data from valid BSW events, the BSW application did not impact the rate of lane change maneuvers. However, this application was very effective in reducing the rate of unsafe outcomes by 77% at the 93% confidence level based on very small counts of unsafe outcomes by both silent and active alert events.

5.5 Intersection Movement Assist

5.5.1 Observed IMA Events

The SDC contained 9,668 IMA events from the NYC CVP deployment. These events comprised 2,862 silent IMA events (30%) and 6,806 active IMA events (70%). Figure 83 illustrates the breakdown of IMA events with silent and active alerts by month during the yearlong deployment. In the before period, there were 1,913 IMA events (20%). In the after period, there were 7,755 IMA events (80%).

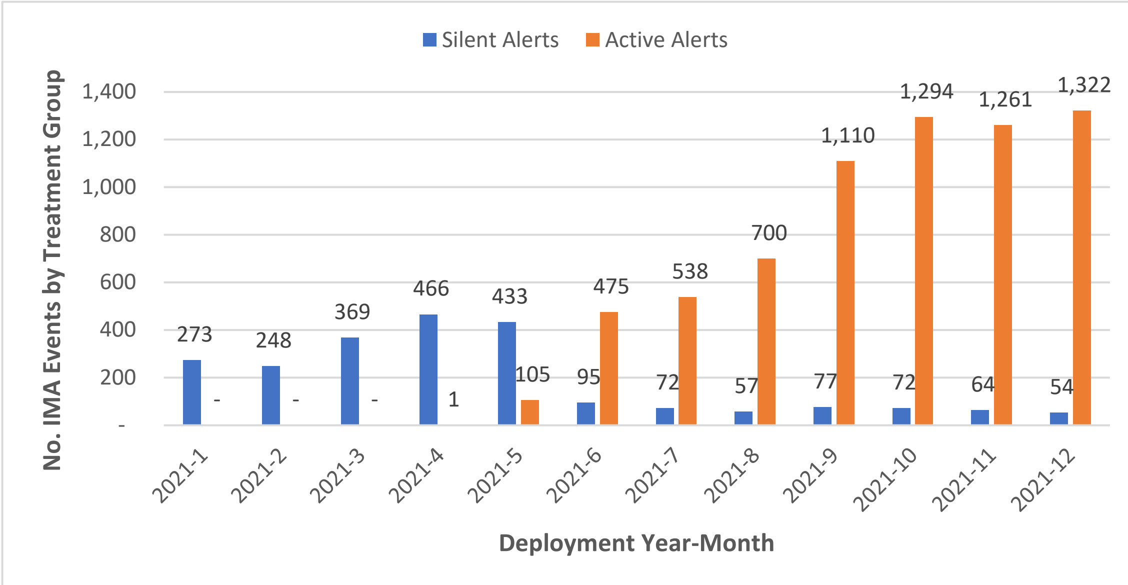


Source: U.S DOT Volpe Center

Figure 83. Distribution of All IMA Events by Alert Status and Deployment Year and Month

5.5.1.1 IMA Events Observed by Treatment Group

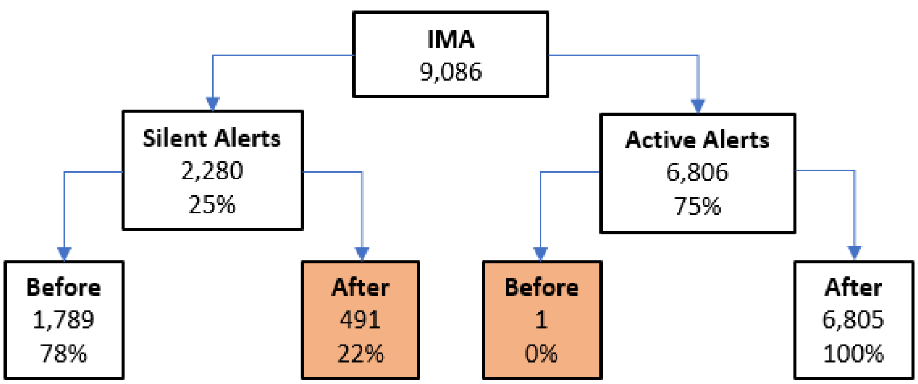
The treatment group received 9,086 IMA events (94% of all IMA events). There were 2,280 silent and 6,806 active IMA events (25% and 75%, respectively, of treatment group IMA events). Figure 84 illustrates the breakdown of IMA events with silent and active alerts for the treatment group by month during the yearlong deployment.



Source: U.S DOT Volpe Center

Figure 84. Distribution of Treatment Group IMA Events by Alert Status and Deployment Year and Month

The before period contained 1,790 treatment group IMA events (20%). The after period contained 7,296 treatment group IMA events (80%). Figure 85 breaks down the number of silent and active alerts by the before and after periods.

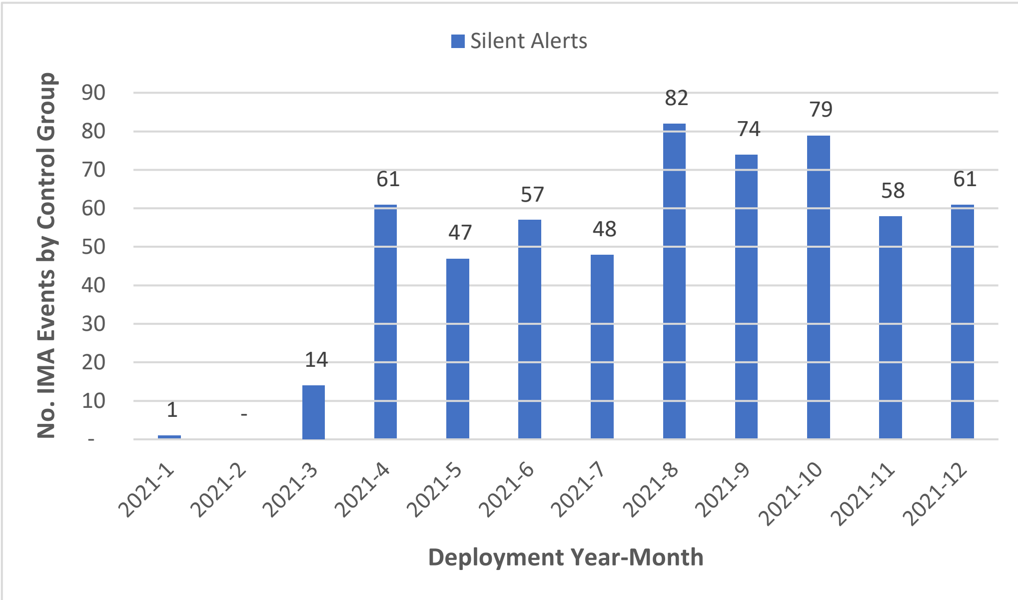


Source: U.S DOT Volpe Center

Figure 85. Breakdown of Treatment Group IMA Events by Alert Status and Deployment Period

5.5.1.2 IMA Events Observed by Control Group

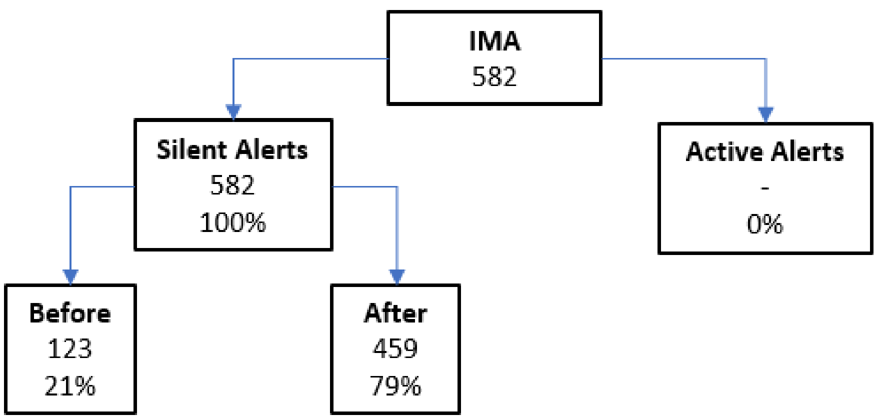
The control group experienced 582 IMA events (6% of all IMA events). These events comprised 51 silent IMA events (100%) and no active IMA events. Figure 86 illustrates the breakdown of IMA events with silent and active alerts for the control group by month during the yearlong deployment period.



Source: U.S DOT Volpe Center

Figure 86. Distribution of Control Group IMA Events by Alert Status and Deployment Year and Month

The before period contained 123 control group IMA events (21%). The after period contained 459 control group IMA events (79%). Figure 87 breaks down the number of IMA events with silent alerts by the before and after periods.



Source: U.S DOT Volpe Center

Figure 87. Breakdown of Control Group IMA Events by Alert Status and Deployment Period

5.5.2 Data Filtering of IMA Events

The Volpe team removed IMA events from the analysis due to data and alert validity issues.

5.5.2.1 IMA Events with Data Issues

The Volpe team removed some IMA events from the analysis due to data collection and processing issues, including:

1. The pre-warning or post-warning recording times were insufficient.
2. The trajectory of the HV or RV was discontinuous or unreasonable.

3. The HV or RV did not have range or relative position data (i.e., the obfuscated GPS data was missing).
4. The HV or RV speed was unrealistic or erroneous (i.e., greater than 24.6 m/s or 55 mph).
5. The HV or RV x-y coordinates indicated it was stationary while its speed was non-zero.

Table 74 indicates the number of discarded IMA events for each filtering condition listed above. Filtering was applied independently of the control and treatment groups, silent and active alerts, and before and after periods. The filtering process removed 6,473 IMA events (67%) of all IMA events. The Volpe team deemed the remaining 3,195 IMA events to be acceptable for further analysis.

Table 74. Filtering Results of IMA Events with Data Issues

Data Quality	Count	Percentage
Insufficient pre- or post-warning times	81	0.8%
Unreasonable Vehicle Trajectory	67	0.7%
Unavailable range data	5,818	60.2%
Speed > 24.6 m/s (55 mph)	374	3.9%
Incorrect X-Y Conversion	133	1.4%
Good Data	3,195	33.0%
Total	9,668	26.6%

5.5.2.2 IMA Events with Invalid Alerts

The Volpe team removed IMA events from the analysis that were deemed to have experienced invalid alerts due to limitations in application capability, including:

1. There was a substantial elevation difference between the HV and RV (based on a minimum vertical clearance for a bridge over a roadway, at least 32.8 ft (10 m)).
2. The HV and RV were not on intersecting paths (i.e., the RV was either not in front of the HV or not approaching it from either the left or right).
3. Either the HV or RV was not traveling on a straight road (i.e., yaw value of > 0.025 rad).
4. The HV and RV were traveling in opposite directions.
5. The HV was turning right AND the RV was approaching from the right. (Note: An alert may be valid if the HV is turning right and the RV is approaching from the left.)

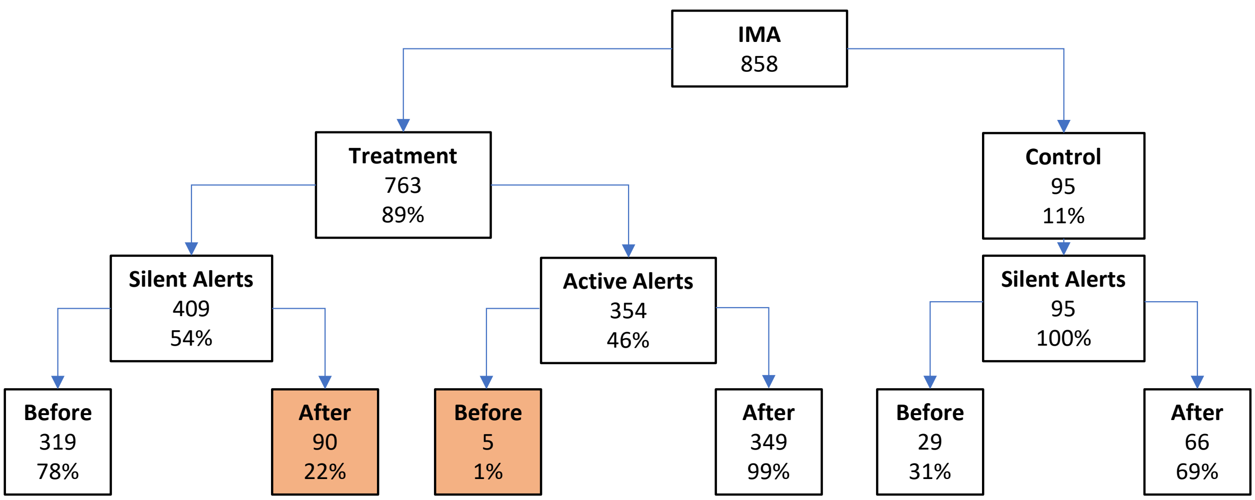
Table 75 indicates the number of discarded IMA events for each filtering condition listed above. Filtering was applied independently of the control and treatment groups, silent and active alerts, and before and after periods. The filtering process removed 2,337 invalid IMA events (73% of the acceptable IMA events). The Volpe team assessed the safety impact of the IMA application based on the remaining 858 IMA events that were deemed to be valid.

Table 75. Filtering Results of IMA Events with Invalid Alerts

Alert Validity	Count	Percentage
Elevation discrepancy	5	0.2%
HV and RV not on Intersecting paths	280	8.8%
HV or RV not on straight path	2,031	63.6%
HV turning right/RV approaching from right	21	0.7%
Valid	858	26.9%
Total	3,195	100.0%

5.5.2.3 IMA Events with Valid Alerts

The filtering of the data yielded 858 IMA events with valid alerts (9% of all observed IMA events). Figure 88 illustrates the breakdown of these events by treatment and control groups, silent and active alerts, and before and after periods.



Source: U.S DOT Volpe Center

Figure 88. Breakdown of Valid IMA Events by Experimental Group, Alert Status, and Deployment Period

The treatment group erroneously received 90 silent alerts in the after period and 5 active alerts in the before period (designated by red cells in Figure 88). These events represent 95 alerts or 12% of all treatment group IMA events with valid alerts. These alerts, while valid, would generally be excluded from the safety impact analysis. The safety impact analysis normally compares the performance of the treatment group in the before period (with appropriately silent alerts) to the after period (with appropriately active alerts).

5.5.3 Valid IMA Data Analysis

The treatment group had 319 valid IMA events with silent alerts in the before period and 349 valid IMA events with active alerts in the after period, accounting respectively for 48% and 52% of all valid IMA events (Figure 101). Overall, the data filtering process resulted in a total of 858 valid IMA events that included 504 (59%) events with silent alerts and 354 (41%) events with active alerts. Consequently, the Volpe team decided to assess the safety impact of IMA by comparing the response between all silent and all active alerts from both the treatment and control groups due to the larger sample size.

5.5.3.1 Initial Conditions of IMA Events

The Volpe team analyzed the following measures of performance for the initial conditions of IMA events:

1. HV time to reach the conflict zone at alert onset (s) ≡ $TTCZ_{HV}(0)$
2. RV time to reach the conflict zone at alert onset (s) ≡ $TTCZ_{RV}(0)$

In order to match the initial conditions of IMA events with silent alerts to active alerts for comparing vehicle/driver response to these alerts, the Volpe team decided to examine the following two samples based on $TTCZ_{HV}(0)$ and $TTCZ_{RV}(0)$ thresholds:

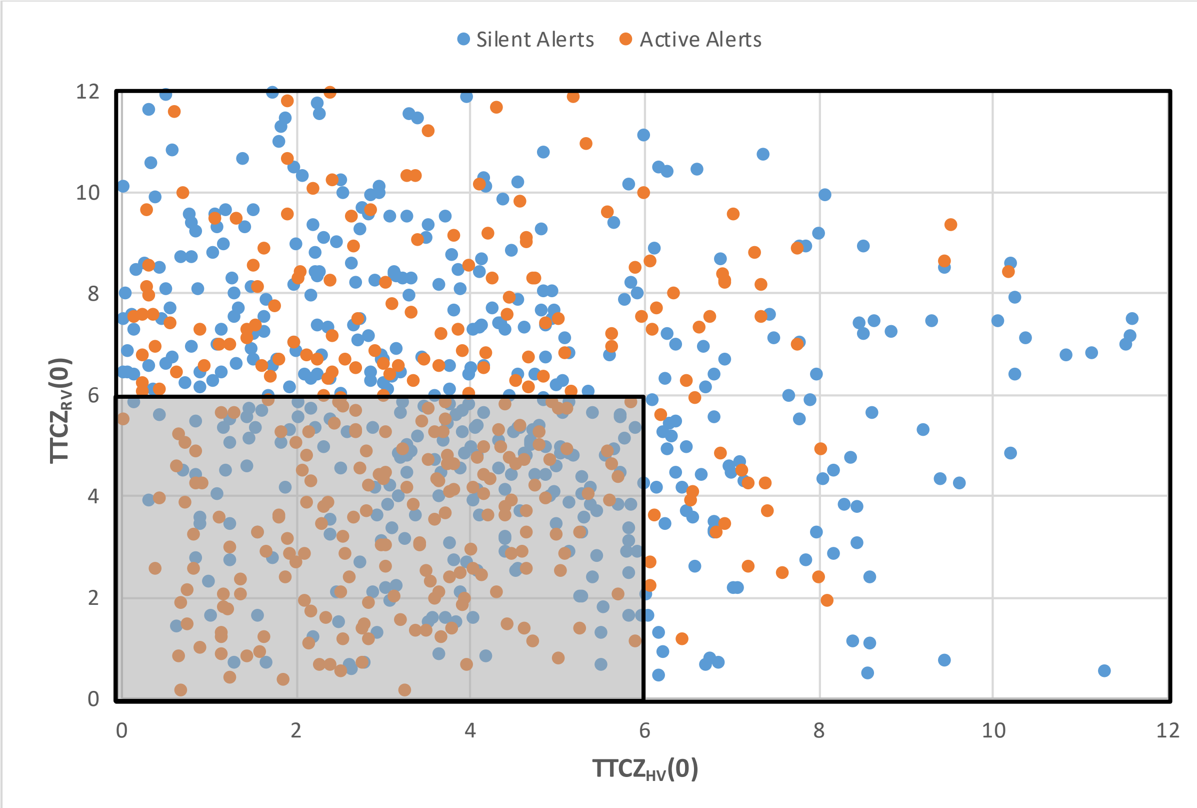
1. IMA events with $TTCZ_{HV}(0)$ less than 12 s and $TTCZ_{RV}(0)$ less than 12 s
2. IMA events with $TTCZ_{HV}(0)$ less than 6 s and $TTCZ_{RV}(0)$ less than 6 s

Table 76 shows the number and percentage of IMA events with silent and active for each of the two analysis samples listed above. The first sample excludes 84 events or about 10% of the total 858 valid IMA events, which received alerts at $TTCZ_{HV}(0)$ and $TTCZ_{RV}(0)$ greater than or equal to 12 s. The second sample excludes 497 events or about 58% of the total 858 valid IMA events, which received alerts at $TTCZ_{HV}(0)$ and $TTCZ_{RV}(0)$ greater than or equal to 6 s.

Table 76. Breakdown of IMA events by ($TTI_{HV}(0)$, $TTI_{RV}(0)$) Thresholds and Alert Status

Alert Status	All TTI	TTI < 12 s	TTI < 6 s	All TTI	TTI < 12 s	TTI < 6 s
Silent	504	451	179	59%	58%	50%
Active	354	323	182	41%	42%	50%
Total	858	774	361	100%	100%	100%

Figure 89 displays the scatter plot of $TTCZ_{HV}(0)$ versus $TTCZ_{RV}(0)$ under 12 s for valid IMA events with silent and active alerts, and highlights the two analysis sets with TTI under 12 s and TTI under 6 s.



Source: U.S DOT Volpe Center

Figure 89. Scatter Plot of $TTCZ_{HV}(0)$ versus $TTCZ_{RV}(0)$ under 12 s in Valid IMA Events

5.5.3.2 Vehicle/Driver Response to IMA Events

The Volpe team categorized the response to valid IMA events into two dynamically-distinct scenarios, based on whether or not the HV entered or crossed the conflict zone. This zone is defined by the overlap of the projected paths between the HV and RV.

Table 77 and Table 78 show the number and percentage of IMA events with silent and active alerts for each of the two response scenarios mentioned above, respectively for the TTI under 12 s and TTI under 6 s analysis samples. The HV entered the conflict zone in slightly more IMA events in TTI at alert onset under 6 s (83%) than TTI under 12 s (81%) samples.

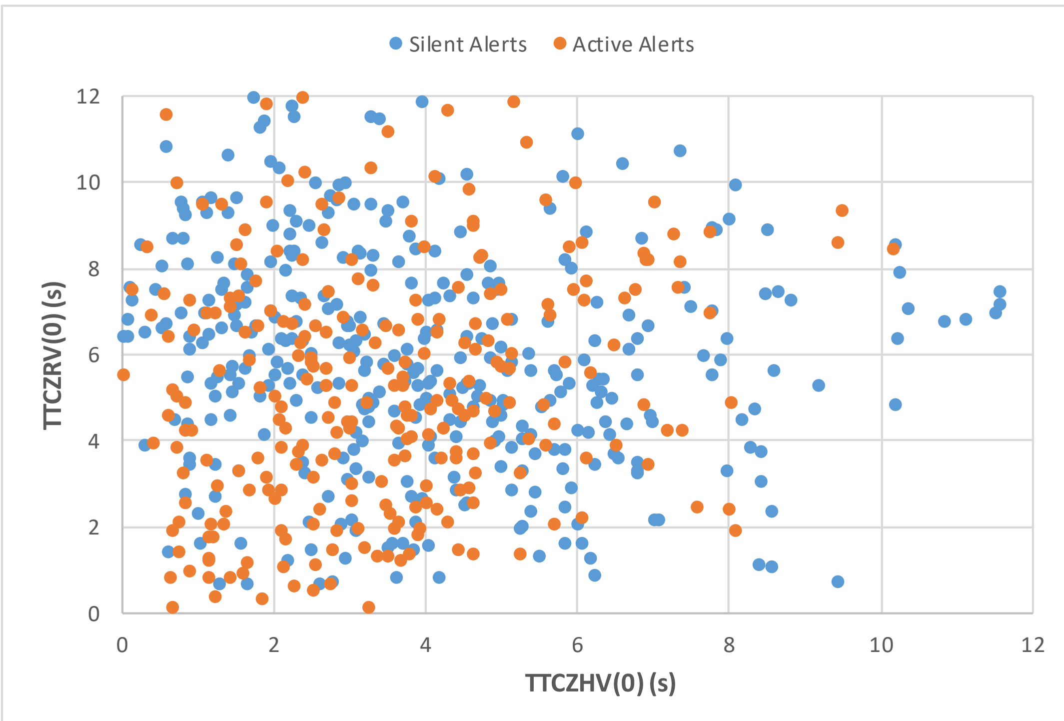
Table 77. Breakdown of IMA events (TTI < 12 s) by HV Entered the Conflict Zone (ECZ) and Not Entered the Conflict Zone (NECZ) and by Alert Status

Alert Status	**ECZ**	**NECZ**	**Total**	**ECZ**	**NECZ**	**Total**
Silent	362	89	451	80%	20%	100%
Active	263	60	323	81%	19%	100%
Total	625	149	774	81%	19%	100%

Table 78. Breakdown of IMA events (TTI < 6 s) by HV Entered the Conflict Zone (ECZ) and Not Entered the Conflict Zone (NECZ) and by Alert Status

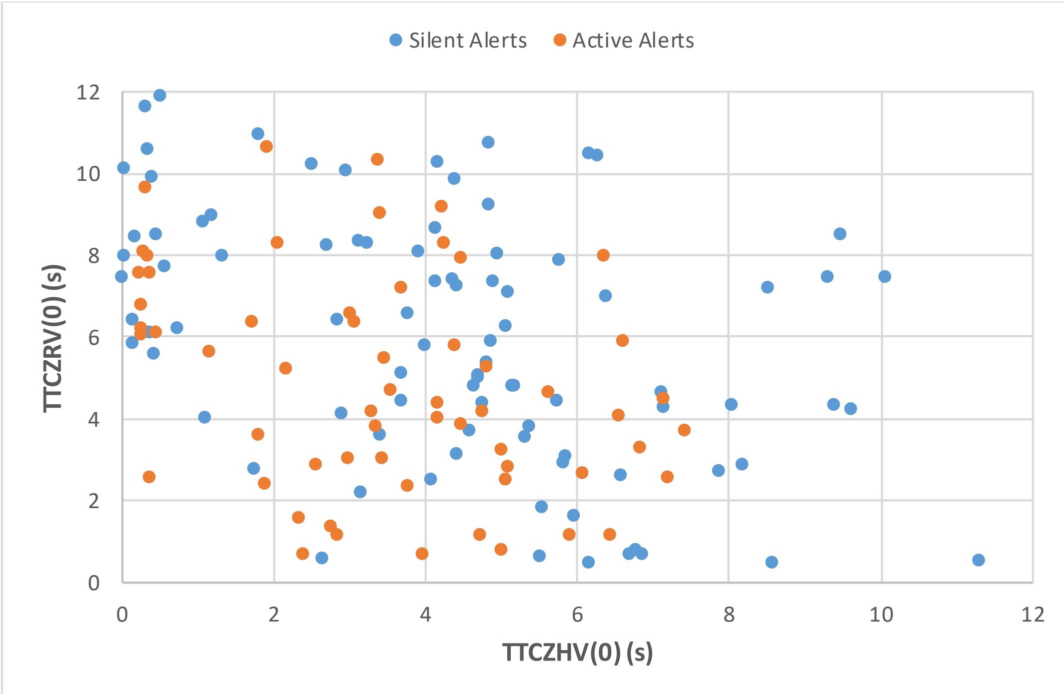
Alert Status	ECZ	NECZ	Total	ECZ	NECZ	Total
Silent	149	30	179	83%	17%	100%
Active	151	31	182	83%	17%	100%
Total	300	61	361	83%	17%	100%

Figure 90 and Figure 91 present the scatter plots of the IMA Event Initial Conditions at Alert Onset that resulted respectively in the HV entering the conflict zone and the HV not entering the conflict zone.



Source: U.S DOT Volpe Center

Figure 90. Scatter Plot of $TTCZ_{HV}(0)$ versus $TTCZ_{RV}(0)$ for the IMA HV Entered Conflict Zone Scenario



Source: U.S DOT Volpe Center

Figure 91. Scatter Plot of $TTCZ_{HV}(0)$ versus $TTCZ_{RV}(0)$ for the IMA HV Did Not Enter Conflict Zone Scenario

5.5.3.2.1 Analysis of IMA Events where HV Entered the Conflict Zone

The measures of performance for vehicle/driver response to IMA alert, which resulted in the HV entering the conflict zone, included the following:

1. Post Encroachment Time (s) ≡ PET
2. Count of events that resulted in an unsafe/safe outcome with PET greater than 3 s, excluding PET under 1 s

The Volpe team decided to remove 96 IMA events from the analysis that resulted in PET values less than 1 s, since they seem unreasonable for the time period in such a naturalistic driving environment.

5.5.3.2.1.1 Analysis of IMA NECZ Events in TTI < 12 s Dataset

Table 79 presents descriptive statistics of PET in the HV Entered the Conflict Zone scenario in response to IMA silent and active alerts for the TTI < 12 s dataset, together with the result of the statistical 2-tailed t-test not assuming equal variances. Excluding PET values under 1 s, IMA events with silent alerts experienced a higher mean PET value of 3.73 s than active alerts with a mean PET value of 3.11 s. This difference of 0.6 s in the mean PET value between IMA events with silent and active alerts is statistically significant at over 98% confidence level. It should be noted that the Volpe team was not able to compute PET in 285 events where the RV did not enter the conflict zone.

Table 79. Statistics of Post Encroachment Time (s) in IMA HV Entered Conflict Zone Scenario by Alert status for TTI < 12 s Dataset

Alert Status	Count	Mean	StdDev	Minimum	Median	Maximum	P(T ≤ t)
Silent	150	3.73	1.98	1.00	3.40	9.20	0.017
Active	94	3.11	1.97	1.00	2.45	8.20	

Table 80 provides the counts and percentages of IMA events that resulted in unsafe and safe outcomes in the ECZ scenario for the TTI under 12 s dataset, in response to silent and active alerts. The percentages reflect the proportion of these events relative to the total number of IMA events in the ECZ scenario. In this case, silent alerts yielded more IMA events with a safe outcome (55%) than active alerts (41%). This difference is statistically significant at the 95% confidence level (P = 0.05) based on the odds ratio test (Odds ratio = 0.59, percent change = -69%, and 95% confidence intervals = 0.35 to 0.99).

Table 80. Count and Percentage of IMA HV Entered Conflict Zone Events with Unsafe/Safe Outcome by Alert Status for TTI < 12 s Dataset

Alert Status	Unsafe	Safe	Total	% Unsafe	% Safe	% Total
Silent	68	82	150	45%	55%	100%
Active	55	39	94	59%	41%	100%
Total	123	121	244	50%	50%	100%

By considering the proportion of events with an unsafe/safe outcome relative to all IMA events (both ECZ and NECZ scenarios) in the TTI less than 12 s dataset, Table 81 still shows that silent alerts yielded slightly more IMA events with a safe outcome (83%) than active alerts (80%). However, this difference is not statistically significant (P = 0.318) based on the odds ratio test (Odds ratio = 1.23, percent change = 18%, and 95% confidence intervals = 0.82 to 1.81).

Table 81. Count and Percentage of All IMA Events with Unsafe/Safe Outcome by Alert Status for TTI < 12 s Dataset

Alert Status	Safe	Unsafe	Total	% Safe	% Unsafe	% Total
Silent	334	68	402	83%	17%	100%
Active	221	55	276	80%	20%	100%
Total	555	123	678	82%	18%	100%

5.5.3.2.1.2 Analysis of IMA ECZ Events in TTI < 6 s Dataset

Table 82 presents descriptive statistics of PET in the HV Entered the Conflict Zone scenario in response to IMA silent and active alerts for the TTI under 6 s dataset, together with the result of the statistical 2-tailed t-test not assuming equal variances. Excluding PET values under 1 s, IMA events with silent alerts experienced a higher mean PET value of 2.94 s than active alerts with a mean PET value of 2.66 s. This difference of about 0.3 s in the mean PET value between IMA events with silent and active alerts is not statistically significant (P = 0.326).

Table 82. Statistics of Post Encroachment Time (s) in IMA HV Entered Conflict Zone Scenario by Alert status for TTI < 6 s Dataset

Alert Status	Count	Mean	StdDev	Minimum	Median	Maximum	P(T ≤ t)
Silent	69	2.94	1.50	1.00	2.70	7.30	0.326
Active	64	2.66	1.74	1.00	2.00	7.10	

Table 83 provides the counts and percentages of IMA events that resulted in unsafe and safe outcomes in the ECZ scenario for the TTI under 6 s dataset, in response to silent and active alerts. The percentages reflect the proportion of these events relative to the total number of IMA events in the ECZ scenario. In this case, silent alerts yielded more IMA events with a safe outcome (41%) than active alerts (30%). This difference is not statistically significant (P = 0.19) based on the odds ratio test (Odds ratio = 0.62, percent change = -62%, and 95% confidence intervals = 0.30 to 1.27).

Table 83. Count and Percentage of IMA HV Entered Conflict Zone Events with Unsafe/Safe Outcome by Alert Status for TTI < 6 s Dataset

Alert Status	Unsafe	Safe	Total	% Unsafe	% Safe	% Total
Silent	41	28	69	59%	41%	100%
Active	45	19	64	70%	30%	100%
Total	86	47	133	65%	35%	100%

By considering the proportion of events with an unsafe/safe outcome relative to all IMA events (both ECZ and NECZ scenarios) in the TTI less than 6 s dataset, Table 84 still shows that silent alerts yielded slightly more IMA events with a safe outcome (72%) than active alerts (68%). However, this difference is not statistically significant (P = 0.434) based on the odds ratio test (Odds ratio = 1.22, percent change = 18%, and 95% confidence intervals = 0.74 to 2.03).

Table 84. Count and Percentage of All IMA Events with Unsafe/Safe Outcome by Alert Status for TTI < 6 s Dataset

Alert Status	Safe	Unsafe	Total	% Safe	% Unsafe	% Total
Silent	107	41	148	72%	28%	100%
Active	96	45	141	68%	32%	100%
Grand Total	203	86	289	70%	30%	100%

5.5.3.2.2 Analysis of IMA Events where HV Did Not Enter the Conflict Zone

The Volpe team analyzed the following measures of vehicle/driver performance in response to IMA alerts in events where the HV did not enter the conflict zone after alert onset:

1. Count of events whether or not the brakes were applied
2. BRT in braking events
3. A_{HV} in braking events

All alerts where drivers did not enter the conflict zone and had a brake response were moving faster than 10 mph.

5.5.3.2.2.1 Analysis of IMA NECZ Events in TTI < 12 s Dataset

Table 85 provides the counts and percentages of IMA events that resulted in brake or no brake application in the NECZ scenario for the TTI under 12 s dataset, in response to silent and active alerts. Silent alerts yielded more IMA events with brake application (26%) than active alerts (18%). This difference is not statistically significant (P = 0.286) based on the odds ratio test (Odds ratio = 0.64, percent change = -55%, and 95% confidence intervals = 0.29 to 1.45).

Table 85. Count and Percentage of IMA HV Did Not Enter Conflict Zone Events by Brake Application and Alert Status for TTI < 12 s Dataset

Alert Status	Brakes Not Applied	Brakes Applied	Total	% Brakes Not Applied	% Brakes Applied	% Total
Silent Alerts	66	23	89	74%	26%	100%
Active Alerts	49	11	60	82%	18%	100%
Total	115	34	149	77%	23%	100%

Table 86 provides the descriptive statistics of BRT and A_{HV} for valid IMA HV NECZ events with brake application in response to silent and active alerts. The 2-tailed t-test, not assuming equal variances, show no statistically-significant difference in A_{HV} between silent and active alerts in valid IMA HV NECZ events. On the other hand, there is a statistically-significant difference in BRT at the 100% confidence level between silent (2.77 s) and active alerts (1.39 s) in valid IMA HV NECZ events. Thus, active IMA alerts were very effective in reducing BRT by 1.38 s that improves the crash avoidance capability of drivers receiving such alerts in crash-imminent situations.

Table 86. Descriptive Statistics and t-Test Results of BRT and AHV for IMA HV NECZ Events with Brake Application by Alert Status for TTI < 12 s Dataset

Measure	Alert Status	Count	Mean	StdDev	Minimum	Median	Maximum	P(T ≤ t)
BRT (s)	Silent	23	2.77	1.30	0.5	2.7	5	0.0015
	Active	11	1.39	0.93	0.1	1.2	2.8	
A_{HV} (m/s^2)	Silent	27	-1.12	2.90	-4.307	-1.88	11	0.1298
	Active	10	-2.03	0.52	-3.16	-1.96	-1.18	

5.5.3.2.2.2 Analysis of IMA NECZ Events in TTI < 6 s Dataset

Table 87 provides the counts and percentages of IMA events that resulted in brake or no brake application in the NECZ scenario for the TTI under 6 s dataset, in response to silent and active alerts. Silent alerts yielded more IMA events with brake application (33%) than active alerts (19%). This difference is not statistically significant (P = 0.22) based on the odds ratio test (Odds ratio = 0.48, percent change = -108%, and 95% confidence intervals = 0.14 to 1.54).

Table 87. Count and Percentage of IMA HV Did Not Enter Conflict Zone Events by Brake Application and Alert Status for TTI < 6 s Dataset

Alert Status	Brakes Not Applied	Brakes Applied	Total	% Brakes Not Applied	% Brakes Applied	% Total
Silent Alerts	20	10	30	67%	33%	100%
Active Alerts	25	6	31	81%	19%	100%
Total	45	16	61	74%	26%	100%

Table 88 provides the descriptive statistics of BRT and A_{HV} for valid IMA HV NECZ events with brake application in response to silent and active alerts. The 2-tailed t-test, not assuming equal variances, show no statistically-significant difference in A_{HV} between silent and active alerts in valid IMA HV NECZ events. On the other hand, there is a statistically-significant difference in BRT at the 98% confidence level between silent (2.86 s) and active alerts (1.63 s) in valid IMA HV NECZ events. Thus, active IMA alerts were very effective in reducing BRT by 1.23 s that improves the crash avoidance capability of drivers receiving such alerts in crash-imminent situations.

Table 88. Descriptive Statistics and t-Test Results of BRT and A_{HV} for IMA HV NECZ Events with Brake Application by Alert Status for TTI < 6 s Dataset

Measure	**Alert Status**	**Count**	**Mean**	**StdDev**	**Minimum**	**Median**	**Maximum**	**P(T ≤ t)**
BRT (s)	Silent	10	2.86	1.16	1.2	2.7	4.9	0.021
	Active	6	1.63	0.73	0.8	1.5	2.7	
A_{HV} (m/s^2)	Silent	9	-2.26	0.89	-4.31	-2.31	-1.16941	0.254
	Active	5	-1.82	0.46	-2.35	-1.83	-1.17958	

5.5.4 IMA Safety Effectiveness

The IMA application was very effective in reducing brake reaction time by about 1.4 s when the HV did not enter the conflict zone, using either the TTI under 12 s or TTI under 6 s datasets.

6 Conclusions

The Volpe team applied its safety impact assessment approach in Figure 6 to 4 V2I and 5 V2V safety applications to evaluate vehicle/driver response to their silent and active alerts during the yearlong NYC CVP deployment. This assessment started with the analysis of 107,609 V2I and 52,680 V2V alert events, accounting respectively for 67% and 33% of the total 160,289 alert events. The SPDCOMP application triggered the most V2I alert events, totaling 91,468 or 85% of all V2I events. On the other hand, the FCW application issued the most V2V alert events, accumulating 36,410 or 69% of all V2V events. The following is a breakdown of the total 160,289 alert events by:

- Alert status: 41% (65,231) with silent alerts versus 59% (95,058) with active alerts
- Deployment period: 32% (51,348) in the before period versus 68% (108,941) in the after period
- Vehicle group: 6% (10,097) by the control group versus 94% (150,192) by the treatment group

Due to data issues in alert events, the Volpe team applied its own and some of NYC CVP team's filters to remove events with bad data from the safety impact analysis. As a result, this data filtering process removed 54,856 events with bad data or 34% of the total alert events: 26,490 or 25% of all V2I events and 28,366 or 54% of all V2V events. Excessive speed flag caused the most dominant error in 21,875 or 83% of all V2I events with bad data, which was simply a programming error in the ASDs. The Volpe team removed 21,751 or 77% of all V2V events with bad data due to insufficient data points after alert onset (recording or storing error in the data acquisition system) and 5,439 or 19% of all V2V events with bad data due to speed over 24.6 m/s (55 mph).

The Volpe team then validated the efficacy of the alerts from 81,119 V2I events and 24,314 V2V events with good data, totaling 105,433 or 66% of the total alert events. Due to the lack of vehicle location information (i.e., GPS coordinates) in alert event data, data issues rather than application errors could have affected the alert validity analysis. This analysis resulted in the removal of 23,010 invalid events or 22% of the total alert events with good data: 3,764 or 5% of all V2I events with good data and 19,246 or 79% of all V2V events with good data. The CSPDCOMP application had the most invalid events, with HV not approaching a curve in 3,272 or 87% of all invalid V2I events. The FCW application had the most invalid events, with RV not in HV's path at alert onset or HV passing through RV after alert onset accounting for 12,330 or 64% of all invalid V2V events. The percentage of invalid alert events relative to all events with good data is as folllows for each application in descending order: CSPDCOMP 99%, FCW 83%, BSW 82%, IMA 73%, LCW 58%, EEBL 16%, SPDCOMPWZ 2%, RLVW 0.3%, and SPDCOMP 0.01%. Overall, the filtering process of eliminating events with bad data and invalid alerts from further analysis yielded the following percentages of removed events relative to all events for each application in descending order: CSPDCOMP 99%, FCW 92%, IMA 91%, BSW 89%, LCW 75%, EEBL 55%, RLVW 41%, SPDCOMP 25%, and SPDCOMPWZ 3%.

After the two event filtering steps, the Volpe team evaluated the safety impact of each safety application on vehicle/driver performance in the NYC CVP site based on the folllowing datasets:

- V2I safety applications: 68,614 SPDCOMP, 4,158 RLVW, 29 CSPDCOMP, and 4,525 SPDCOMPWZ valid events.
- V2V safety applications: 2,844 FCW, 247 EEBL, 794 LCW, 325 BSW, and 858 IMA valid events.

The safety impact analysis normally compares the performance of the treatment group in the before period with silent alerts to the after period with active alerts. During the NYC CVP deployment, the treatment group erroneously received 1,790 active alerts in the before period and 3,622 silent alerts in the after period. These alerts, while valid, would generally be excluded from the safety impact analysis. Consequently, the number of events with silent alerts was much smaller than the number of events with active alerts for most applications (except SPDCOMP) that it inhibited the ability to perform a meaningful statistical comparison of the treatment group performance between the before and after periods. The Volpe team then decided to assess the safety impact of all applications, other than SPDCOMP, by comparing the response between all valid events with silent alerts and all valid events with active alerts, regardless of period (before or after) or vehicle group (treatment or control).

The Volpe team devised and computed many measures of performance to assess vehicle/driver response to alerts from the various safety applications. While conducting this assessment, the Volpe team found unreasonable values by some measures, such as many events with PET under 1 s or TaR over 6 s. Such events were then removed from the analysis of application safety effectiveness. Key results of this analysis, exhibiting statistically-significant difference in vehicle/driver response between events with silent and active alerts, are provided below for each application:

- SPDCOMP
  - 16% increase in speed limit compliance, from 71% by the treatment-before/silent group to 77% by the treatment-after/active group (P = 0.00).
- RLVW
  - 41% reduction in red light violation rates, from 16.1% with silent alerts to 9.5% with active alerts (P = 0.00)
  - Reduction in brake reaction time by 0.4 s when the HV did not enter the intersection after alert onset, from 2.9 s with silent alerts to 2.5 s with active alerts (P = 0.01).
- CSPDCOMP
  - Reduction in minimum speed by 3.6 m/s, from 13.6 m/s with silent alerts to 10.0 m/s with active alerts (P = 0.00) based on a very small count of events in each group.
  - Increase in speed differential by 1.5 m/s, from 0.9 m/s with silent alerts to 2.4 m/s with active alerts (P = 0.00) based on a very small count of events in each group.
- SPDCOMPWZ
  - Increase in minimum speed of 0.2 m/s, from 5.6 m/s with silent alerts to 5.8 m/s with active alerts (P = 0.03).
  - Decrease in speed differential by 0.2 m/s, from 2.0 m/s with silent alerts to 1.8 m/s with active alerts (P = 0.10).
- FCW
  - Reduction in brake reaction time in the LVD scenario by 0.13 s, from 1.21 s with silent alerts to 1.08 s with active alerts (P = 0.08).
  - Slight reduction in average deceleration in the LVD scenario by 0.08 m/s^2, from 2.33 m/s^2 with silent alerts to 2.25 m/s^2 with active alerts (P = 0.08).
  - 25% reduction in near-crash rate in the LVD scenario, from 14.6% with silent alerts to 11.0% with active alerts (P = 0.07).
- EEBL

    - Reduction in brake reaction time by 0.4 s, from 1.4 s with silent alerts to 1.0 s with active alerts ($P = 0.03$).
    - Reduction in average deceleration by 0.17 m/s^2, from 2.24 m/s^2 with silent alerts to 2.07 m/s^2 with active alerts ($P = 0.08$).
- LCW
    - 12% reduction in lane change rate, from 53% with silent alerts to 46% with active alerts ($P = 0.07$).
    - 46% reduction in unsafe lane change rate, from 8% with silent alerts to 4% with active alerts ($P = 0.04$).
- BSW
    - 77% reduction in unsafe lane change rate, from 4% with silent alerts to 1% with active alerts ($P = 0.07$) with very small counts of unsafe outcome by both groups.
- IMA
    - Reduction in post encroachment time by 0.6 s, from 3.7 s with silent alerts to 3.1 s with active alerts ($P = 0.02$) under the initial condition dataset of $TTCZ_{HV}(0)$ under 12 s and $TTCZ_{RV}(0)$ under 12 s. This result points to unsafe response to IMA alerts; however, the initial condition dataset of $TTCZ_{HV}(0)$ under 6 s and $TTCZ_{RV}(0)$ under 6 s did not show any difference for this measure.
    - Reduction in brake reaction time by 1.4 s when the HV did not enter the conflict zone, from 2.8 s with silent alerts to 1.4 s with active alerts ($P = 0.002$) under the initial condition dataset of $TTCZ_{HV}(0)$ under 12 s and $TTCZ_{RV}(0)$ under 12 s. Similarly, the initial condition dataset of $TTCZ_{HV}(0)$ under 6 s and $TTCZ_{RV}(0)$ under 6 s resulted in a reduction by 1.3 s, from 2.9 s with silent alerts to 1.6 s with active alerts ($P = 0.02$).

In summary, the Volpe team deduced an increase in speed limit compliance by SPDCOMP, reduction in red light violation rate by RLVW, reduction in near-crash rate in the LVD scenario by FCW, reduction in lane change rate by LCW, and reduction in unsafe lane change rate by LCW and BSW. These changes to vehicle/driver performance in response to alerts from these applications directly lead to potential safety benefits from their deployment. In addition, the reduction in brake reaction time in response to RLVW, FCW, EEBL, and IMA alerts enhances the safety performance of drivers and indirectly contributes to potential safety benefits of these applications.

Finally, the Volpe team recommends the following future analyses to better understand the impact of the deployed safety applications on vehicle/driver performance:

- Safety analysis by vehicle type
- Performance trend or adaptation over time
- Performance analysis by driving factors (time of day, weather, lighting, geographical locations)
- Sensitivity analysis of various parameters with different thresholds (TaR, PET)
- Sensitivity analysis of initial conditions, especially for RLVW and IMA
- Analysis between treatment-before/silent and treatment-after/active groups for applications other than SPDCOMP, given sufficient sample sizes.

7 REFERENCES

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Appendix A. Functions of NYC CVP Safety Applications

A.1. V2V Safety Applications

A.1.1. FCW

This V2V application informs the driver about a slowed or stopped vehicle ahead in the traffic, even when the driver's view is obstructed by other vehicles, road curvature, or bad weather conditions. Whether the vehicle ahead is moving slow (slower speed, in the process of acceleration, or decelerating) or is completely stationary, FCW evaluates a potential threat and issues warnings accordingly. In addition, the following conditions must be met in order to trigger FCW alerts:

- Distance between the HV and RV is less than or equal to 250 m (820.2 ft)
- Lateral separation between the HV and RV is less than or equal to 2 m (6.6 ft)
- Heading difference between the HV and RV is between -22.5 and 22.5 degrees
- RV is in a forward gear

A.1.2. EEBL

This V2V application informs the driver about a hard braking event by a vehicle ahead in the traffic, even when the driver's view is obstructed by other vehicles or bad weather conditions. EEBL enables a vehicle to broadcast a self-generated emergency brake event to surrounding vehicles. Upon receiving such event information, the HV determines the relevance of the event and provides an alert to the driver, if appropriate. In addition, the following conditions must be met in order to trigger EEBL alerts:

- HV speed is greater than or equal to 1 m/s (2.2 mph)
- RV speed is greater than or equal to 4 m/s (8.9 mph)
- Distance between the HV and RV is less than or equal to 250 m (820.2 ft)
- Time to collision between the HV and RV is less than or equal to 7 s
- Deceleration of RV is less than or equal to -3.5 m/s^2 (-11.5 ft/s^2)
- Lateral separation between the HV and RV is less than or equal to 5 m (16.4 ft)

A.1.3. LCW and BSW

The LCW V2V application warns the driver when it is not safe to change lane due to high collision probability with other RVs. LCW generates BSW advisory alerts if an RV is inside the configured Blind Spot zone. The following are some conditions that must be met in order to trigger alerts:

- HV speed is greater than or equal to 8 m/s (17.9 mph)
- RV speed is greater than or equal to 8 m/s (17.9 mph)
- HV steering wheel angle is between 10 and 90 degrees.

A.1.4. IMA

This V2V application warns the driver when it is not safe to enter an intersection due to high collision probability with other RVs. It also checks if entering HV is crossing the intersection. Only the entering HV receives an alert, when proceeding from a stop with RV approaching from the side. Both HV and RV receive the alert when HV and RV are approaching the intersection from cross directions. Some of the conditions for this application are:

- Distance to collision above which IMA alerts are not raised is 250 m (820 ft)
- Speed above which to classify the HV/RV as ‘crossing’ intersection is 6.69 m/s (15 mph)
- Speed above which to classify the HV/RV as ‘entering’ intersection is 0.1 m/s (0.22 mph)
- Acceleration used to determine whether it's a stationary vehicle/moving vehicle is 0.2 m/s^2 (0.66 ft/s^2)
- Speed above which to inhibit IMA alerts is 29 m/s (65 mph)
- HV deceleration seen to inhibit alert is 0.3 m/s^2 (1 ft/s^2)

A.2. V2I Safety Applications

A.2.1. SPDCOMP

This V2I application triggers an alert when either HV exceeds the recommended speed by a configured amount or for a configured period of time by time of day. Minimum HV speed above which the application monitors vehicle speed and issues alerts is 3 m/s (6.7 mph).

A.2.2. CSPDCOMP

This V2I application advises the driver in time to reduce vehicle speed to the posted speed limit before the vehicle enters the curve, if the vehicle speed is greater than the posted curve speed. While the HV is in the curve, the application alerts the driver when HV speed exceeds the posted speed plus the excessive curve speed amount threshold for a time period exceeding the excessive curve speed time threshold. The threshold values are:

- Advisory activation distance before the curve is 50 m (164 ft)
- Advisory activation time before the curve is 5 s
- Warning activation distance before the curve is 30 m (98 ft)
- Warning activation time before the curve is 2.5 s
- Excess Speed Threshold above the limit is 4.47 s (10 mph)
- Excess Time Threshold above the limit is 1 s

A.2.3. SPDCOMPWZ

This V2I application advises the driver in time to reduce vehicle speed to the posted speed limit before the vehicle enters the zone, if the vehicle speed is greater than the reduced speed zone.

A.2.4. RLVW

This V2I application triggers a driver alert for an HV approaching a signalized intersection when it determines that a stop is required and the HV will violate the Red Light stop bar at a signalized intersection based on its current speed, heading, acceleration, location and the location of stop bars.

A.2.5. OVCCLEARANCELIMIT

This V2I application advises the driver of a potential crash before the bridge, overpass, or tunnel to allow the HV to exit the restricted roadway and find an alternate route. This application warns the driver of an impending crash before the over-height bridge, overpass, or tunnel to stop the vehicle completely and avoid the crash.

A.2.6. EVACINFO

This V2I application transmits the information from NYC Office of Emergency Management and from NYCDOT Office of Emergency Response to the connected vehicles near or within affected areas during incidents. When incidents occur, emergency response information will be transmitted to the connected vehicles through the roadside equipment and drivers will be notified if the are within the designated warning zone.

A.2.7. PEDINXWALK

This V2I application monitors the vehicle's location, heading, and speed, and issues a warning to the driver if they determine that an impact is likely with a pedestrian in the crosswalk.

Appendix B. MAP and SPaT Data Processing for RLVW Application

The NYC CVP data included the MAP and SPaT datasets, in addition to the Event and BSM records, which support the complete analysis of RLVW events. The MAP data describe the geometric layout of intersections relevant in an RLVW event. The SPAT data give signal phasing and timing information for intersections and lanes during an RLVW event.

For each RLVW event record, there is one MAP record that describes the geometry of all the intersections around the location where an RLVW event was triggered. SPaT records are recorded by the vehicle ASD system at a resolution of 10 Hz, similar to BSM data. In practice however, SPaT records were not received by equipped vehicles every tenth of a second. Rather, SPaT records were recorded in the NYC CVP data on average about once every 0.4 s across all RLVW events.

The Volpe team took a number of steps to process and connect the MAP and SPaT data to BSM data that contained HV trajectories during an RLVW event. The following subsections describe these processing and analysis steps.

B.1. Joining Tables and Import Data

The raw MAP and SPAT data available in the SDC were organized into a number of tables that need to be joined together before importing into the Volpe team's separate SQL database.

B.1.1. Joining MAP Data

The existing MAP data tables were organized into seven different tables that contain various parameters relevant to the geometry and layout of the intersections through which the HV drove before, during, and after an RLVW event. Figure 92 shows the structure of these tables and the connections between the parameters.

The "MAP_INTERSECTIONS_LANESET_NODES" table stores the geometry of each lane in the intersection as a list of nodes. Each node represents the distance in X and Y coordinates from the previous node in the list of nodes. Distances are given in units of centimeter (cm). The first node represents the distance in X and Y coordinates from the reference point of the intersection, which is stored in the "MAP_INTERSECTIONS" table. Each row of the "MAP_INTERSECTIONS_LANESET_NODES" table represents a single node and thus only contains one non-null value in the columns labelled "DeltaNode…."

To make the data easier to analyze, the first step in MAP data processing takes each record in the "MAP_INTERSECTIONS_LANESET_NODES" table and collapses nodes of a single lane into a list structure containing pairs of X and Y distance values for each node. This creates a new table with one record per lane in each intersection. The X and Y delta values are converted from cm to m in this step as well. Then, the X and Y distances for each node are converted to absolute X and Y coordinates within the overall coordinate system of the event with the datum point at the HV location at alert onset time.

After these conversions, important columns from the various MAP tables are extracted and joined to the core MAP table to form a final MAP dataset representing the geometries of each lane within each intersection in each RLVW event record. Columns are also renamed to more descriptive names that are easier to interpret when performing data queries. Table 89 presents the structure of the final table of MAP messages.

MAP_CORE	DataType
EventID	Varchar
MapID	Varchar
EventType	Varchar
SeqNum	INT
MapRecactMsgHeaderMyrfLevel	INT
MapRecactMsgHeaderAuthenticated	BOOLEAN
MapRecactMapMsgLayerType	STRING(255)
MapRecactMapMsgLayerID	INT

MAP_INTERSECTIONS	DataType	Units
InterID	Varchar	
MapID	Varchar	
IntersectionID	Varchar	
IntersectionRefPointX	float	m
IntersectionRefPointY	float	m
IntersectionRefPointZ	float	m
IntersectionLaneWidth	int	

MAP_INTERSECTIONS_LANE_SET	DataType
InterID	Varchar
MapID	Varchar
LaneID	Varchar
LanesetLaneID	INT
LanesetIngressApproach	INT
LanesetLaneAttributesDirectionalUse	STRING(255)
LanesetLaneAttributesSharedWidth	STRING(255)
LanesetLaneAttributesLaneTypeBikeLane	STRING(255)
LanesetManeuvers	STRING(255)

MAP_INTERSECTIONS_SPEEDLIMITS	DataType	Units
InterID	Varchar	
MapID	Varchar	
SpeedLimitType	STRING(255)	
SpeedLimitSpeed	DOUBLE	m/s

MAP_INTERSECTIONS_TMP (JASON FORMAT)	DataType	Units
InterID	Varchar	
MapID	Varchar	
intersections	XXXX	

MAP_INTERSECTIONS_LANESET_CONNECTSTO	DataType	Units
InterID	Varchar	
MapID	Varchar	
LaneID	Varchar	
ConnectingLaneLane	INT	
ConnectingLaneManeuver	STRING(255)	
SignalGroup	INT	
ConnectionID	INT	

MAP_INTERSECTIONS_LANESET_NODES	DataType
InterID	Varchar
MapID	Varchar
LaneID	Varchar
DeltaNodexy1_X	int
DeltaNodexy1_Y	int
DeltaNodexy2_X	int
DeltaNodexy2_Y	int
DeltaNodexy3_X	int
DeltaNodexy3_Y	int
DeltaNodexy4_X	int
DeltaNodexy4_Y	int
DeltaNodexy5_X	int
DeltaNodexy5_Y	int
DeltaNodexy6_X	int
DeltaNodexy6_Y	int
AttributesdWidth	int
AttributesdElevation	int

Source: U.S DOT Volpe Center

Figure 92. Data structure for RLVW MAP Data

Table 89. Final MAP Data Structure Imported into Volpe Team's SQL Database

MAP_CORE	**DataType**
EventID	Varchar
MapID	Varchar
EventType	Varchar
InterID	Varchar
IntersectionID	Varchar
ReferencePoint_X	float
ReferencePoint_Y	float
ReferencePoint_Z	float
LaneWidth	int
LanesetLaneID	Varchar
SignalGroup	INT
ConnectionID	INT
DeltaNodeList	List of XY tuples

B.1.2. Joining SPAT Data

The existing SPaT data tables were organized into five different tables that contain various parameters relevant to the signal status at every recorded time point during an RLVW event. Records in the table represent the signal status for each lane entering the intersection. Figure 93 shows the structure of these tables and the connections between the parameters.

Important columns for Volpe team's data analysis were extracted from each of the tables in Figure 93 and joined together to form a final SPaT data table. No other conversions or reformatting were performed for the SPaT data elements. Columns are also renamed to more descriptive names that are easier to interpret when performing data queries. Table 90 presents the structure of the final table of SPaT messages.

Table 90. Final SPaT Data Structure Imported into Volpe Team's SQL Database

SPAT_CORE	**DataType**
EventID	Varchar
SpatID	Varchar
EventType	Varchar
InterID	Varchar
IntersectionID	Varchar
Time	float
SignalGroup	int
ConnectionID	int
SignalState	Varchar

SPAT_CORE	DataType
EventID	Varchar
SpatID	Varchar
EventType	Varchar
SeqNum	int
SpatRecordMsgHeaderMyrfLevel	int
SpatRecordMsgHeaderAuthenticated	BOOLEAN

SPAT_INTERSECTIONS	DataType
InterID	Varchar
SpatID	Varchar
IntersectionID	Varchar
IntersectionRevision	INT
IntersectionStatus	STRING(255)
IntersectionTime	INT

SPAT_INTERSECTIONS_STATES	DataType
InterID	Varchar
SpatID	Varchar
StateID	Varchar
SignalGroup	int

SPAT_INTERSECTIONS_STATES_MANEUVERASS	DataType
InterID	Varchar
SpatID	Varchar
StateID	Varchar
ConnectionID	int
QueueLength	int
AvailableStorageLength	int
WaitOnStop	BOOLEAN
PedBicycleDetect	BOOLEAN

SPAT_INTERSECTIONS_STATES_STATETIMESPEED	DataType
InterID	Varchar
SpatID	Varchar
StateID	Varchar
EventState	Varchar
TimingConfidence	int
TimingMaxEndtime_s	float
TimingMinEndtime_s	float
TimingLikelyTime_s	float

Source: U.S DOT Volpe Center

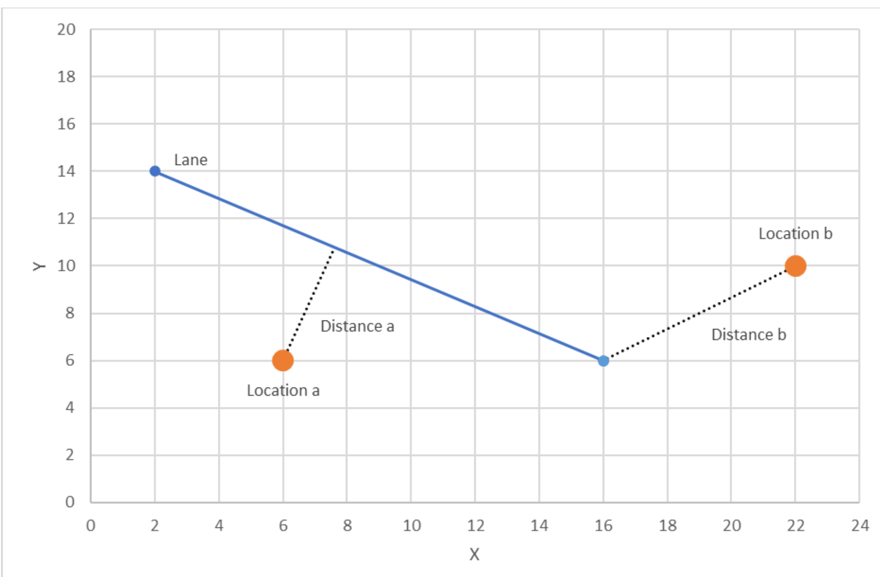
Figure 93. Data Structure for RLVW SPaT Data

B.2. Connecting MAP and SPaT Records to BSM Data

In order to effectively analyze RLVW event data for safety effectiveness, it was necessary to evaluate the signal status that applied to the HV at each point in time recorded before, during, and after an RLVW event. In addition, it was necessary to estimate the HV's distance to the intersection stop line at each point in time during an RLVW event. This required determining the lane in which the HV was located at alert onset time. The next sub-section describes how this distance was calculated.

B.2.1. Calculating Vehicle Distance to Lane

The Volpe team used built-in geometric evaluation functions in Microsoft's SQL Server system to determine the smallest distance between any lane in the MAP record for a particular RLVW event. This was computed as the shortest distance between the point of vehicle location and any point within the line segment geometry of a lane. Thus, if the vehicle was between the endpoints of the lane geometry, the distance was calculated as the perpendicular distance between the vehicle location at the lane. However, if the vehicle was beyond the endpoints of the lane, the distance was calculated between the vehicle location and the closest endpoint of the lane geometry. Figure 94 visually illustrates this calculation methodology. Location a is between the two lane endpoints; thus, the distance is measured as the perpendicular distance between the vehicle location and the lane. Location b is outside of the lane endpoints; thus, the distance is measured as the distance between the vehicle location and the closest lane endpoint.



Source: U.S DOT Volpe Center

Figure 94. Measurement of Distance between Vehicle and Lane

B.2.2. Determining the Applicable Lane

When determining the lane applicable to each RLVW event record, the Volpe team looked only at the vehicle's location at alert onset time. For each RLVW event, the distance was calculated to each lane in the applicable MAP record, according to the procedure described previously. A vehicle was considered to potentially be in a lane if the distance calculated to the lane was less than 3 m. Once all lanes within 3 m were identified, the lane with the shortest distance to the vehicle location at the time of the event was determined to be the lane in which the vehicle was located. The lane and intersection identification fields in the MAP data for this specific lane were assigned to the BSM records in a new table so that information could be easily retrieved for those lanes in later analysis steps.

B.2.3. Assigning Signal States to BSM Data

The next important step is to determine the applicable signal status throughout the duration of the RLVW event. The signal status for the lane in which the vehicle was located at the time of the event is taken from the SPaT data tables in Volpe team's database. SPaT data records signal states at tenth of a second intervals surrounding an RLVW event. The signal states are encoded to communicate slight differences in right of way between different types of red, yellow, and green lights. To simplify the analysis, the Volpe team simplified these codes to just indicate if the light was red, yellow, or green. Table 91 shows these codes and the equivalent red, yellow, or green status.

Table 91. Signal Status Codes and Meanings

Signal State Code	Light Status
dark	Light off
permissive-Movement-Allowed	Green
protected-clearance	Yellow
protected-Movement-Allowed	Green
stop-And-Remain	Red
stop-Then-Proceed	Flashing Red
unavailable	Not available

While available at 10 Hz resolution, the SPaT data often have large gaps for a particular RLVW event. As discussed previously, SPaT messages are available every 0.4 s on average across all RLVW events. The gaps in RLVW data range from a few tenths of a second to large gaps between 1 and 4 s. In order to analyze RLVW events, the Volpe team filled signal status information for points in time where SPaT data were not available with the last known value of signal status. This step produced a complete dataset with lane and signal status information for BSMs associated with RLVW event data.

B.2.4. Assigning Stop-Line Location to BSM Data

Another important parameter to consider when analyzing RLVW data was the location of the stop line for the lane in which the vehicle was located at the time of the alert. The stop line for RLVW data was assumed to be the end-point of the lane in which the vehicle was located at the time of the RLVW event closest to the center of the intersection. The geometric coordinates of this end point were stored in the BSM table as a separate data field.

Once the RLVW stop line is assigned for each BSM record, relative kinematic information can be calculated to determine the following measures:

1. Time to intersection (with the stop line)
2. Relative heading
3. Signal state at time of crossing the stop line
4. Latitudinal and longitudinal ranges to the stop line
5. Range rate to the stop line

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